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6 CONCEPT EXPLORATION—
AN APPROACH TO SMALL WARSHIP DESIGN,

10 M.C. Eames   T.G. Drummond

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ABSTRACT

This paper describes a versatile tool for the designer of small warships (1000 - 6000 tons), intended for use in the opening phase of the design process. Known as a "concept exploration model", it provides an alternative approach to the usual immediate reliance on a "basis ship", enabling the designer to explore a wider range of design concepts.

To calculate performance and other design characteristics from an assumed set of ship dimensions, a simple algorithm has been developed using data derived from a number of successful small warships. This has been programmed for a high-speed computer in such a way that a search can be made over a wide range of assumed dimensions, to determine a hypothetical "optimum ship" for specified operational objectives. More importantly, the trends of design behaviour around that optimum are clearly illustrated.

The concept exploration model is an advanced slide-rule, intended to relieve the designer of drudgery, and to provide him data in the quantities made possible by modern computers, yet in a form he can assimilate. In no way does the model relieve him of decision-making responsibility. Nor does it compete with more extensive computer-based methods developed for subsequent phases of the design process.

RESUME

Cet exposé traite d'un instrument extrêmement maniable, conçu pour venir en aide au concepteur de petits navires de guerre jaugeant entre 1000 et 6000 tonneaux, dans la phase initiale du processus du tracé du plan. Connu sous l'appellation de "gabarit d'exploration conceptuelle", il fournit une solution de rechange au "navire de base", sur lequel on a coutume de s'appuyer, et il permet au concepteur d'explorer davantage l'univers des possibilités du dessin naval.

Pour calculer, à partir d'un ensemble présupposé de dimensions, la performance et les autres points caractéristiques du navire sur plan, on a mis au point un algorithme simple qui utilise les données empruntees à un certain nombre de petits navires de guerre qui ont fait leurs preuves. On a programmé ces données pour une calculatrice rapide, de façon à pouvoir explorer un vaste champ de dimensions hypothétiques et arriver ainsi à déterminer le navire "optimal" hypothétique qui répond à des objectifs opérationnels spécifiques. Ce qui est encore plus important, c'est que les tendances du comportement du prototype autour de cet optimum se trouvent nettement définies.

Le gabarit d'exploration conceptuelle est une règle à calcul d'avant-garde qui évite au concepteur des opérations mathématiques fastidieuses et qui lui fournit des données d'un ordre de quantités que seules permettent les calculatrices modernes, tout en étant sous une forme qu'il peut assimiler. L'instrument en question ne le dégage aucunement de la responsabilité de prendre des décisions. Il ne rivalise pas non plus avec les méthodes automatisées de plus grande envergure mises au point pour les phases subséquentes du processus d'élaboration des plans.

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Concept Exploration—an Approach to Small Warship Design

by M. C. Eames, B.Sc., M.Eng.* (Fellow) and T. G. Drummond, B.A.Sc., S.M., N.E.* (Visitor)

Read in London at a meeting of the Royal Institution of Naval Architects on April 7, 1976, Mr B. N. Baxter, M.Sc., Ph.D. (Vice President) in the Chair.

London (England)

SUMMARY: This paper describes a versatile tool for the designer of small warships (1000-6000 tons), intended for use in the opening phase of the design process. Known as a 'concept exploration model', it provides an alternative approach to the usual immediate reliance on a 'basis ship', enabling the designer to explore a wider range of concepts.

To calculate performance and other design characteristics from an assumed set of ship dimensions, a simple algorithm has been developed using data derived from a number of successful small warships. This has been programmed for a computer in such a way that a wide range of assumed dimensions can be searched, to determine a hypothetical optimum ship for specified operational objectives. More importantly, the trends of design behaviour around that optimum are clearly illustrated.

1. INTRODUCTION

1.1 The Process of Preliminary Design

The most satisfactory method of warship design that has evolved is essentially a process of making judicious changes to an existing successful ship for which reliable data are available. This so-called 'basis ship' is chosen to possess performance characteristics as close as possible to those demanded by the new operational requirements, to minimise departures from the factual security of the data base.

Since the classical calculations of naval architecture attack the analysis rather than the design problem, iteration is involved in seeking those changes needed to meet the operational objectives. Fig. 1 shows a simplified form of the 'design spiral' popularly used to illustrate this process. The first turn of the spiral, labelled CONCEPT EXPLORATION, in fact represents many turns; all the iterations the designer takes to arrive at a first set of ship dimensions meeting the objectives.

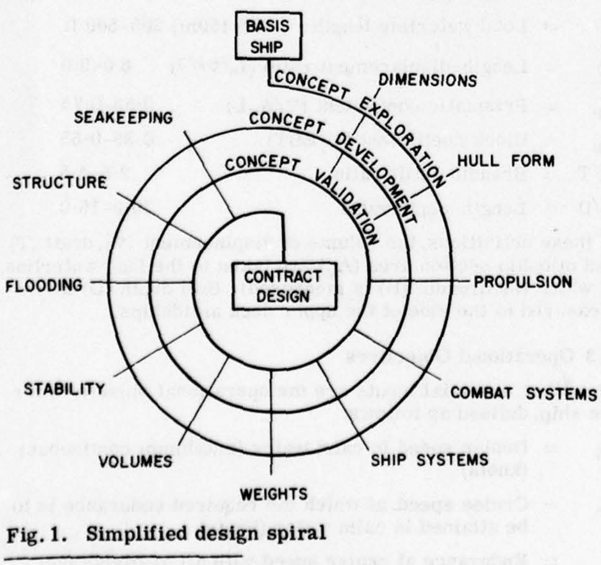

Fig. 1. Simplified design spiral

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Transfer to the CONCEPT DEVELOPMENT phase is often indistinct, but in principle, once the designer has arrived at a satisfactory set of dimensions, he can confirm many assumptions he had to make in the exploratory stage, and so can enter a deeper level of detail in all his calculations. This second turn of the spiral will then hopefully involve only a few iterations before the design is frozen for CONCEPT VALIDATION. This single turn of the spiral completes the preliminary design. The stage has just been reached at which reasonable cost estimates can be attempted, and the overall effectiveness of the ship assessed by the operational staff.

Clearly, if the designer has a good basis ship, and if the new requirements do not entail major departures from it, this is a reliable and rapid method. Indeed, the basis ship approach is mandatory for the concept development and validation phases. There is no other way of obtaining data to the required level of detail. Correct selection of the basis ship is therefore fundamental to the whole process, yet this is the opening move in which the designer is guided only by his past experience.

One obvious shortcoming of the traditional process, then, is the immediate reliance it places on a somewhat arbitrary choice of basis ship. In particular, if the designer is presented with operational requirements that differ radically from those of any previous ship in his data bank, he will be unable to choose his basis ship with confidence.

Another potential problem is the lack of absolute standards. The designer is continually checking his proposals against the basis ship, but he has no way of assessing how closely he is approaching an optimum design. Without new tools he cannot explore enough cases to be certain he has made all his changes in the best possible way. The experienced designer can be confident of producing a good ship, but he will be the first to admit that a better one might have eluded him.

The traditional approach tends to inhibit innovation in the concept exploration stage. The most adventurous designer is constrained by his awareness that reliability decreases as he departs from the basis ship. Time may also constrain him to changes that converge rapidly to a satisfactory solution.

1.2 Objectives of the C.E. Model

Seeking an approach to overcome these shortcomings, DREA has developed a tool known as a C.E., or concept exploration

model. This paper describes the first example, which is suitable for gas turbine powered warships having displacements between 1000 and 6000 tons. The C.E. model provides a rapid way of exploring all reasonable boundaries of dimensions and hull form as the opening move in the design process. It is comparatively crude but, used with intelligent caution, it can assist the designer:

(a) To select the most appropriate basis ship, effectively delaying this selection to the start of the concept development phase.

(b) To estimate dimension and form changes needed to meet the operational requirements with minimal penalties.

(c) By providing a standard of comparison against which to evaluate his results throughout the design process.

In over-simplified terms, a designer seeks the ship of least cost that will carry the required combat systems at the required speed over the required range. In practice this idea of transport cost effectiveness has to be tempered by the arrangeability of the ship, its suitability for handling combat systems, its habitability and many other factors, but it is a reasonable criterion for a first look. Moreover, true costs cannot be assessed with the data initially at hand. Experience has shown that size and acquisition cost are closely related, and even a warship's complement (the largest component of operating cost) is statistically related to ship size.

It follows that a sensible objective for concept exploration is to find the minimum size of ship required to achieve a given payload, speed and range. Clearly, to explore trends over the full range of likely dimensions rather than make minor changes to a basis ship, many hundreds of circuits of the design spiral are needed, and some form of automation becomes essential.

Aware of the pitfalls this introduces, the authors emphasise that the C.E. model described here in no way relieves the designer from decision-making responsibility. It serves as a tool to relieve him of drudgery, to enable him to make a more soundly based start, and to concentrate his energies on matters requiring his judgement and expertise. There are many optional inputs to the model that enable the designer to tailor it to his needs. Approximate, statistically based coefficients used initially can be replaced with more accurate values as his design proceeds. More generally, the model has been formulated to be simple to modify as new data become available or as additional features are suggested by user experience.

While this flexibility extends its usefulness into the concept development phase, the C.E. model is not intended to compete with more extensive computer based models developed for subsequent phases of design (e.g. Ref. 1). It is a complementary tool for primary use in concept exploration.

2. OPERATING MODES AND INPUTS

2.1 Operating Modes

The model can be used in two modes to suit different objectives:

(a) To DESCRIBE the design and performance of ships having specified dimensions and other characteristics input by the designer.

(b) To SEARCH for the minimum sized ship having specified performance.

Use in the SEARCH mode is the true process of concept exploration, as described above. However, having found the minimal ship by this means, a practical designer will want to explore specific variations suggested by his experience, before he is satisfied. The DESCRIBE mode is used for this, and for applications in subsequent phases of the design process.

Both modes use the same essential algorithm, which takes a set of ship dimensions and performs the usual calculations of naval architecture, in simplified form, to arrive at a description of the ship and its performance; once around the design spiral, so to speak. This algorithm is described in Sections 3, 4 and 5. The modes differ in the manner in which they repeat this basic calculation to accomplish their purpose, and consequently in their inputs (Section 2) and outputs (Section 6).

In the DESCRIBE mode the designer inputs the essential dimensions of each ship he wishes to calculate. He can input as many cases as he wishes. The computer operates on each case identically and outputs all the results consecutively. In the SEARCH mode, on the other hand, the designer only specifies the boundaries of dimensions between which he wishes to explore, sets the step sizes for the search, and chooses any of three possible search criteria. The computer examines all possible combinations of dimensions in turn, but only pursues calculations for those meeting specific constraints (Section 6.2). Full results are output for only a few of the best ships accepted, ordered according to the search criterion selected.

A matrix type of search was selected over more sophisticated optimisation processes for three reasons. It is inherently simple, requiring no derivatives or complex logic of local and global moves. It is well adapted to problems where one or more local optima may exist in addition to the global optimum. Finally, and most significantly, a matrix search provides the designer with knowledge of trends in all directions rather than along a narrow path to the optimum. Because of the many facets of practical design swallowed up by simplifying assumptions, the chance of the C.E. model's optimum ship becoming the final design is small indeed. The trends and trade-offs around the optimum point are more important to the designer than a precise definition of the optimum itself.

2.2 Independent Variables

To meet the needs of rapid exploration, seeking comparative rather than absolute values, the model should be the simplest one capable of defining important trends. In particular, the number of independent variables has to be restricted to make practical a full matrix type of search.

Only the essential dimensions of the ship are treated as independent variables. These are most conveniently expressed in non-dimensional form, except for ship length, which is used as the scaling factor throughout. Advisable limits on their variations are set by the spread of the available data base. The independent variables and the limits suggested by the data now programmed are:

L	=	Load waterline length	(60-150m) 200-500 ft
Ⓜ	=	Length-displacement ratio ($L/\nabla^{1/3}$)	6·0-9·0
C_P	=	Prismatic coefficient ($\nabla/A_M L$)	0·55-0·75
C_B	=	Block coefficient (∇/LBT)	0·35-0·65
B/T	=	Breadth-draft ratio	2·5-4·5
L/D	=	Length-depth ratio	10·0-15·0

In these definitions, the volume of displacement (∇), draft (T) and midship section area (A_M) are taken to the load waterline, at which the breadth (B) is measured). Hull depth (D) is measured to the side of the upper deck amidships.

2.3 Operational Objectives

The other essential inputs are the operational objectives for the ship, defined as follows:

v_d = Design speed in calm water (maximum continuous) (knots)

v_e = Cruise speed, at which the required endurance is to be attained in calm water (knots)

E = Endurance at cruise speed with all available fuel used (nautical miles)

H_W = Significant wave height of maximum sea in which the ship is to be fully operational (ft)

For the SEARCH mode, it is also necessary to specify:

W_{uo} = Minimum acceptable operational load (tons)

V_{uo} = Minimum acceptable operational volume (cu ft)

'Operational load' is defined in terms of the standard weights classification system used by Canadian Forces. Essentially, it comprises all armament, ammunition, aircraft, command and control equipment, and any other military payload.

2.4 Optional Inputs

Other factors that the designer may wish to vary are treated as optional inputs. Those currently programmed are listed in Table I. If the designer does not specify any or all of these factors, the computer assumes the 'default' values shown, based on analyses of good current practice.

TABLE I. OPTIONAL INPUTS

NOTATION	PARAMETER DESCRIPTION	DEFAULT VALUE
C_W	Waterplane area coefficient	$0{\cdot}44 + 0{\cdot}52\ C_p$
F_o	Minimum freeboard amidships	$0{\cdot}04$ L
c	Compartmentation standard	3
n_b	No. of watertight bulkheads	$[L/(10+0{\cdot}04L)]-1$
n_d	No. of decks below upper deck	$(D/8)-1$
n_s	No. of propeller shafts	2
n_g	No. of electrical generators	4
P_g	Electrical power installed	Δ (KW)
P_{ge}	Average cruise electrical power	$0{\cdot}25\ P_g$
w	Density of hull material	$0{\cdot}219$ (ton/ft^3)
σ	Yield strength of hull material	$18{\cdot}0$ (ton/in^2)
L_s	Superstructure length	$0{\cdot}5$ L
V_s	Superstructure volume	$0{\cdot}25\ V_T$
V_x	Extra basic volume	0
W_x	Extra basic weight	0
z_x	VCG of extra basic weight	0.65 D
z_u	VCG of operational load	$0{\cdot}70$ D
N	Ship's complement	$m\Delta^{2/3}$
m	Maintenance factor	$1{\cdot}1$

In the SEARCH mode, the selected values will apply to all cases examined in that search. If a designer wishes to vary some of the optional inputs systematically, he must set up his own matrix and use the DESCRIBE mode.

2.5 Optimisation Criteria

For the final ordering of SEARCH results the designer currently has a choice of three criteria, and may select any or all of them simultaneously.

(a) Maximum operational weight ratio (W_u/Δ)

(b) Maximum operational volume ratio (V_u/V_T)

(c) Maximum transport effectiveness (see Section 4.9)

These have been established for initial convenience. With minor programming changes, the designer can set up any function of the output parameters as a criterion for ordering his results. The possible future addition of a cost criterion is discussed in Section 7.2.

Two other inputs are required for the SEARCH mode, to control the number of cases accepted as ships of reasonable size. The designer specifies 'gate factors' on the minimum operational load and volume. For example, if he requires a ship with an operational load of 400 tons, he has no wish to be swamped with results for ships carrying 600 tons. If he sets a gate factor of 1·2, the program will output only cases having a calculated operational load between 400 and 480 tons.

3. HULL FORM DEFINITION

3.1 Waterplane Coefficients

The principal hull dimensions and form coefficients are defined by the independent variables. However, to define the waterplane adequately for stability estimates, empirical expressions are needed for its area and transverse inertia coefficients (C_W and C_{It}). Fig. 2 shows the expression for C_W due to Hovgaard[2], classically recommended for warships, together with available data for modern small warship

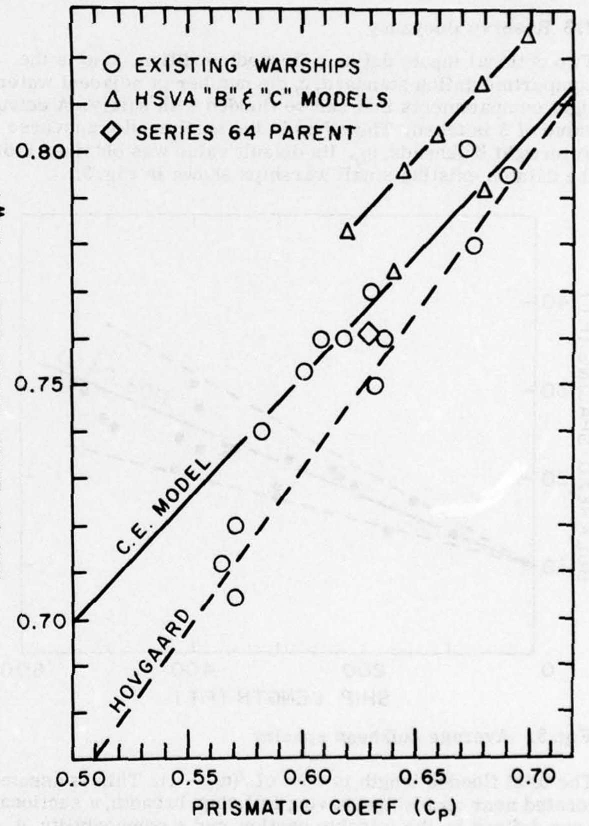

Fig. 2. Waterplane area coefficient

hulls. Included are the systematically varied models of the HSVA 'C' Series[3], defining a typical rate of change of C_W with C_P more clearly. This slope was adopted in preference to that of Hovgaard, but with an intercept chosen in light of the data for existing ships. The selected expression is,

$$C_W = 0{\cdot}44 + 0{\cdot}52\ C_P \qquad (1)$$

Fewer data are available for the inertia coefficient. The usual empirical expression for warships, again due to Hovgaard, appears to overestimate C_{It} slightly, and a constant deduction of 0·003 was conservatively adopted:

$$C_{It} = C_W(0{\cdot}0727C_W + 0{\cdot}0106) - 0{\cdot}003 \qquad (2)$$

C_W is treated as an optional input. The designer can override equation (1) by inputting a specific value of C_W. This input would then also be used in equation (2) to calculate C_{It}.

3.2 Intact Stability

KB is first estimated by the *Morrish formula*, in the form,

$$KB = T(5/6 - C_B/3C_W) \tag{3}$$

BM is simply calculated as,

$$BM = C_{It}B^2/C_BT \tag{4}$$

and KG is obtained from the weight estimates (Section 5.12), to define the metacentric height, GM. A deduction is then made for the effect of free liquid surfaces, taken as 3% of the maximum allowable KG, as defined below.

Roll period is estimated by the well known approximation,

$$T_\phi = 1{\cdot}108\ k_t/\sqrt{GM} \quad \text{sec} \tag{5}$$

using the corrected GM and a radius of gyration, k_t, of 0·4B, (both in ft).

3.3 Reserve Buoyancy

Two optional inputs define a *flooded condition. One* is the compartmentation standard, c, the number of adjacent watertight compartments that can be flooded with safety. A default value of 3 is taken. The other is the number of transverse watertight bulkheads, n_b. Its default value was obtained from the data on existing small warships shown in Fig. 3.

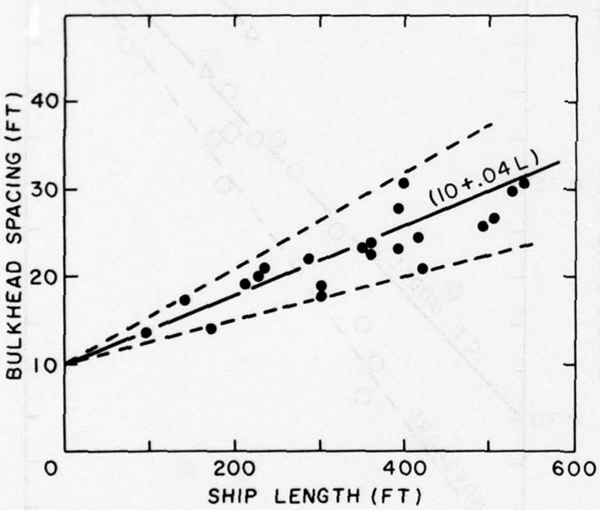

Fig. 3. Average bulkhead spacing

The total flooded length is then $cL/(n_b + 1)$. This is assumed located near amidships, having full ship-breadth, a sectional area defined by the midship section, and a permeability of 84%.

The minimum freeboard, F_1, needed to regain the buoyancy lost by this flooding, is calculated ignoring the flare of the hull above the waterline. It follows that,

$$F_1 = \frac{C_M T}{\dfrac{C_W(n_b + 1)}{0{\cdot}84c} - 1} \tag{6}$$

3.4 Damaged Stability

If the increase in KB is conservatively ignored, the loss of BM due to this flooding is also the minimum value of intact GM required to ensure positive stability in the damaged condition.

Thus the minimum allowable GM is simply,

$$GM_O = \frac{0{\cdot}07cB^2}{C_BT(n_b + 1)} \tag{7}$$

and this is used to define the maximum allowable height of the centre of gravity, KG_O.

3.5 Wetted Surface

For estimating resistance, a method of calculating wetted surface is required, intermediate between the usual determination of girths, which requires a lines plan, and various approximate formulae which do not adequately account for the major hull shape parameters. A new method has been developed[4], expressing wetted surface as a function of L, $\textcircled{M}$, C_P, C_M and B/T.

The first step is to estimate the wetted girth of the midship section, G, as a function of B/T and C_M. The method advocated in Ref. 4 is to adopt the appropriate *Lewis form section*, but the C.E. model uses the following approximation.

$$\frac{G}{T} = C_M\frac{B}{T} + \frac{\pi}{2} \quad \text{for } C_M > \frac{\pi}{4}$$

$$= C_M + \left(\frac{B}{T} + 1\right)\frac{\pi}{4} \quad \text{for } C_M < \frac{\pi}{4} \tag{8}$$

Then the wetted surface can be expressed in the form,

$$\textcircled{S} = \textcircled{M}^2\, C_P{}^{2/3}\left(\frac{G}{T} + \delta\right)\frac{T}{L} \tag{9}$$

where δ is a correction depending on the form of the stern. This correction was expected to depend on the ratio of transom breadth to maximum breadth, but analysis of available data did not justify introducing this extra variable. It suggested reasonable average values of:

δ = 0·42 for transom sterns

δ = 0·30 for cruiser sterns

3.6 Seakeeping Considerations

In the present model, seakeeping is represented only by four simple factors, (Sections 3.7-3.10). Research at DREA is now directed towards developing seakeeping criteria based on predictions of vertical accelerations, slamming and deck wetness. To do this adequately at the concept exploration stage, the hull must be defined by more than the six independent variables used here; the current DREA seakeeping formulation employs 13.

The question to be resolved is the importance of these additional parameters as independent variables. If several of them should be varied systematically, it may prove advisable to have a separate seakeeping model, to be run after the existing C.E. model has narrowed the search somewhat. However, results to date suggest that only one additional variable, C_W, has a major effect on seakeeping, within the practical limitations of conventional hull proportions. If this remains valid on further exploration, it will be tempting to combine the two models.

3.7 Freeboard Criterion

The minimum allowable freeboard amidships, expressed as a fraction of the length, F_O/L, is an optional input. If the designer does not specify this, a standard value of 0·04 is assumed, typical of small warships known to be dry. This is then compared with the F_1/L value needed for reserve buoyancy, and the larger is used to define the minimum allowable hull depth.

Note that the present model does not recognize sheer and therefore includes no criterion for adequate bow freeboard.

3.8 Midship Section Limit

In early versions of the model, optimum ships sometimes emerged with midship sections significantly fuller than current design practice would suggest, being driven by a search for maximum volume within given dimensions. Although there may be a true pointer here for the design of volume

limited warships, present ideas of seakindly hull forms do require the midship section to be eased, particularly at higher design Froude numbers. Pending further research on the benefits and penalties of high midship section coefficient, an arbitrary upper limit has been imposed of $C_M = 0{\cdot}933$ for design Froude numbers below 0·35, and $C_M = 0{\cdot}833$ above 0·48, with linear variation between. This allows some margin over current design practice but restricts abnormal forms.

3.9 Length-Displacement Limit

On the assumption that severe pitching occurs when a ship is in synchronism with waves equal to or greater than the ship in length, Lewis(5) has established an empirical relationship between length-displacement ratio and the maximum Froude number attainable without severe motions. An approximation of Lewis' curve for head seas gives the following estimate of synchronous pitching speed (with L in ft),

$$v_R = 0{\cdot}2239\sqrt{L}\,(\textcircled{M} - 3{\cdot}5) \text{ knots} \qquad (10)$$

This is used in the model, both to calculate synchronous pitching speed for the input $\textcircled{M}$ value, and to impose a limit on the acceptable value of $\textcircled{M}$ in a search. The limit is based on the idea that required cruise speed, v_e, should not exceed synchronous pitching speed by more than 20%. (This holds the drop in average speed to 5% if head storm seas are encountered 25% of the time; a reasonable but arbitrary choice.)

Then the minimum allowable length-displacement ratio is,

$$\textcircled{M}_o = 3{\cdot}5 + 12{\cdot}5\, F_{ne} \qquad (11)$$

where F_{ne} is the Froude number at cruise speed, v_e.

3.10 Speed Loss in Waves

The above criterion should ensure that speed will not have to be reduced significantly below cruise speed under storm conditions. In the operational sea state, specified by the input wave height, H_w, there will be occasions when the ship must be driven well beyond cruise speed. In the absence of ship motion criteria, it is of interest to estimate the maximum speed made possible in these waves by power limitations. An empirical expression developed by Lloyd at AEW is used for this purpose. This is,

$$v_w/v_d = 1 - 50(H_w/L)^2\{1/F_{nd} - 3(H_w/L)^{1/4}\} \qquad (12)$$

where F_{nd} is the Froude number at design speed v_d, and v_w is the maximum speed in the operational sea state.

It is important to distinguish between the two rough water speeds, v_R and v_w. v_w is the speed in waves corresponding to maximum power, but there is no guarantee that ship motions will allow this to be reached, particularly if the designer specifies a large wave height. v_R is the speed at which the ship will start to be in synchronism with head seas large enough to cause severe motions, and this will be closer to cruise speed. The practicality of maintaining speeds between v_R and v_w is a question being addressed by the on-going studies of seakeeping criteria.

4. PERFORMANCE ESTIMATION

4.1 Residuary Resistance

The C.E. model covers too wide a range of design speeds to use the results of any one standard series of model tests. One of three methods is chosen, depending on the Froude number at design speed.

In the highest speed regime, $F_{nd} > 0{\cdot}75$, the model uses data which are effectively a condensation and combination of results from the SSPA(6) and NPL(7) series for high-speed displacement hulls. Figs. 4, 5 and 6 show the faired curves that are tabulated in the computer program, defining a residuary resistance coefficient, $R_R/\Delta F_n^2$, as a function of F_n for contours of $\textcircled{M}$, and for three values of B/T. Linear interpolation is used (and extrapolation for extreme values of B/T). These diagrams are presented at a useful scale because data in this convenient form are scarce.

Both series were run at constant prismatic coefficients;

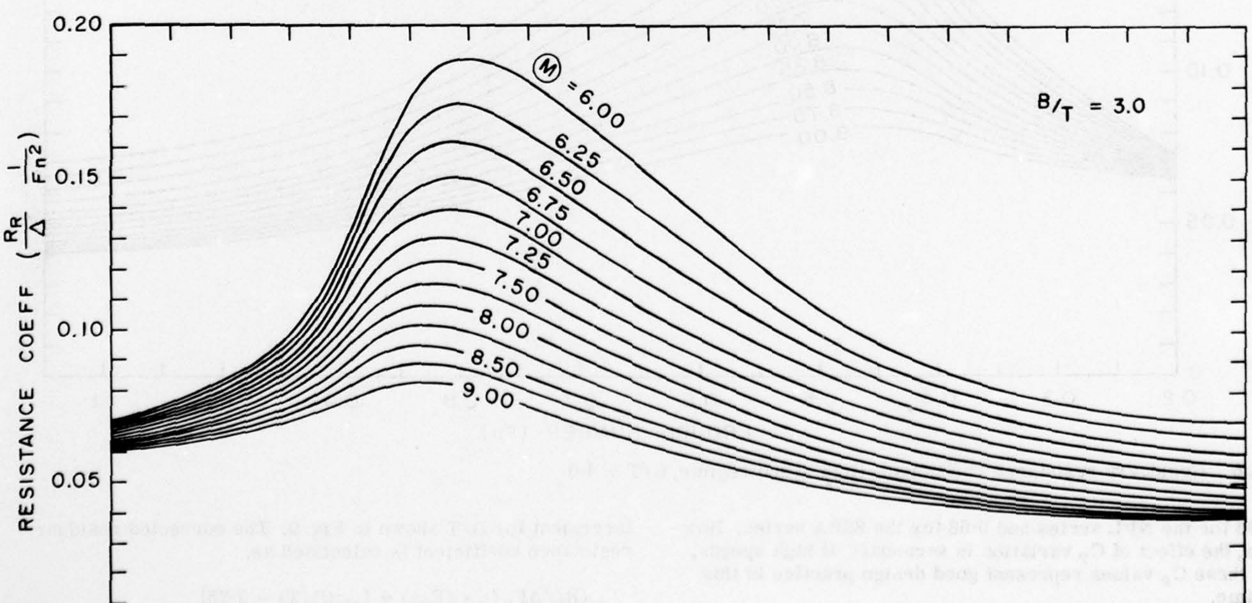

Fig. 4. Residuary resistance coefficient—High speed regime, B/T = 3·0

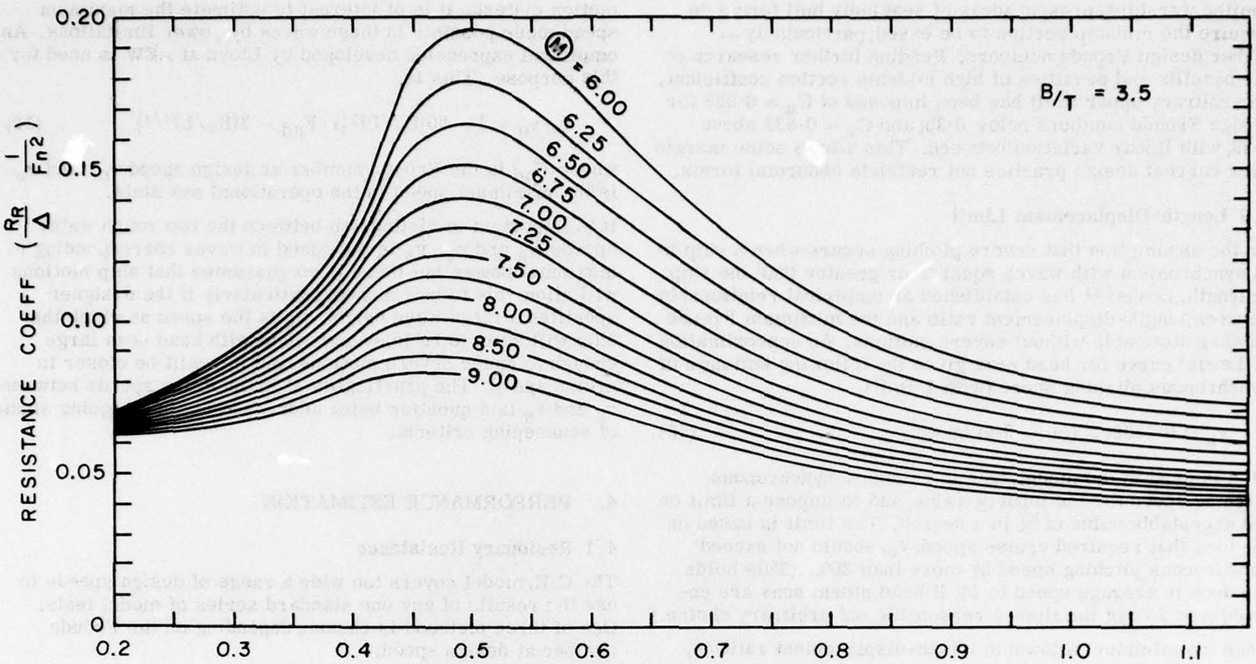

Fig. 5. Residuary resistance coefficient—High speed regime, B/T = 3·5

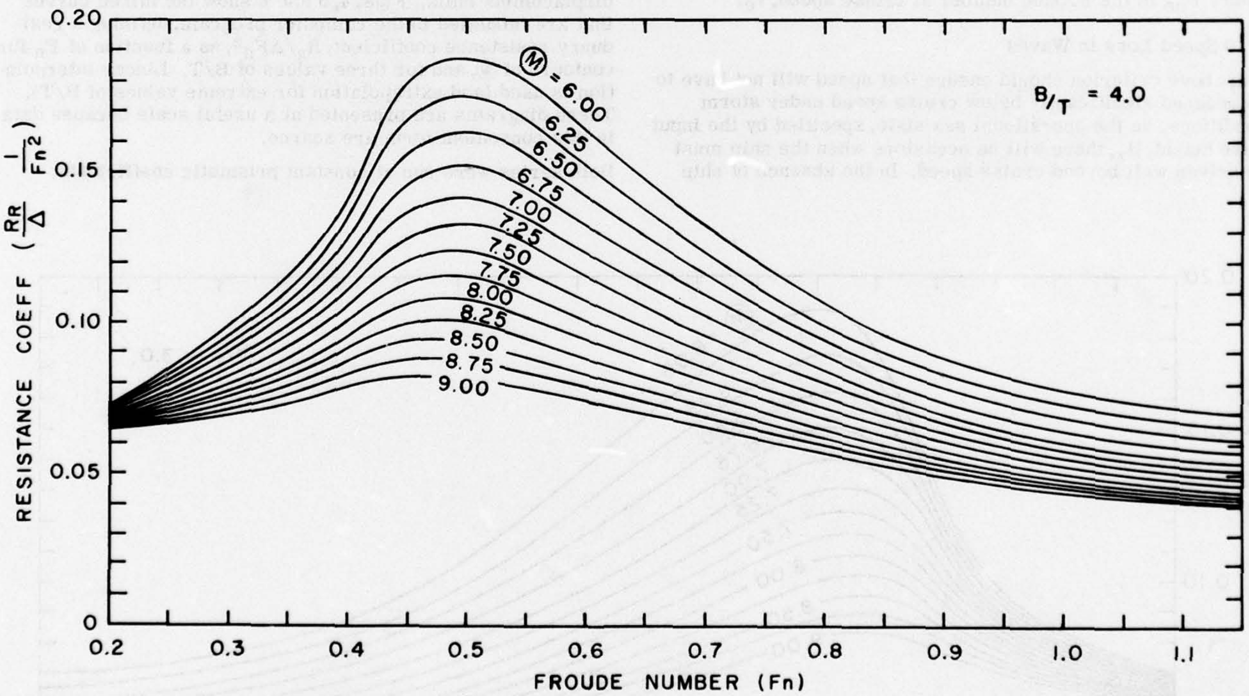

Fig. 6. Residuary resistance coefficient—High speed regime, B/T = 4·0

0·693 for the NPL series and 0·68 for the SSPA series. However, the effect of C_P variation is secondary at high speeds, and these C_P values represent good design practice in this regime.

In the intermediate speed regime, $0{\cdot}30 < F_{nd} < 0{\cdot}75$, most common for small warships, the model uses data derived from the HSVA 'C' series[3]. These are stored in a slightly different form. Fig. 7 shows the basic curves of $R_R/\Delta F_n^2$ for a central case: $C_P = 0{\cdot}645$, B/T = 3·75. There is then a correction factor for C_P variation, shown in Fig. 8, and a small increment for B/T shown in Fig. 9. The corrected residuary resistance coefficient is calculated as:

$$\underset{\text{Fig. 7}}{(R_R/\Delta F_n^2)} \times \underset{\text{Fig. 8}}{(F_{CP})} + \underset{\text{Fig. 9}}{I_{BT}}\{(B/T) - 3{\cdot}75\}$$

In the low speed regime, $F_{nd} < 0{\cdot}30$, the model uses Taylor standard series data[8], which are tabulated for values of Ⓜ (actually C_V), C_P and B/T, over the required F_n range. Linear interpolation is used.

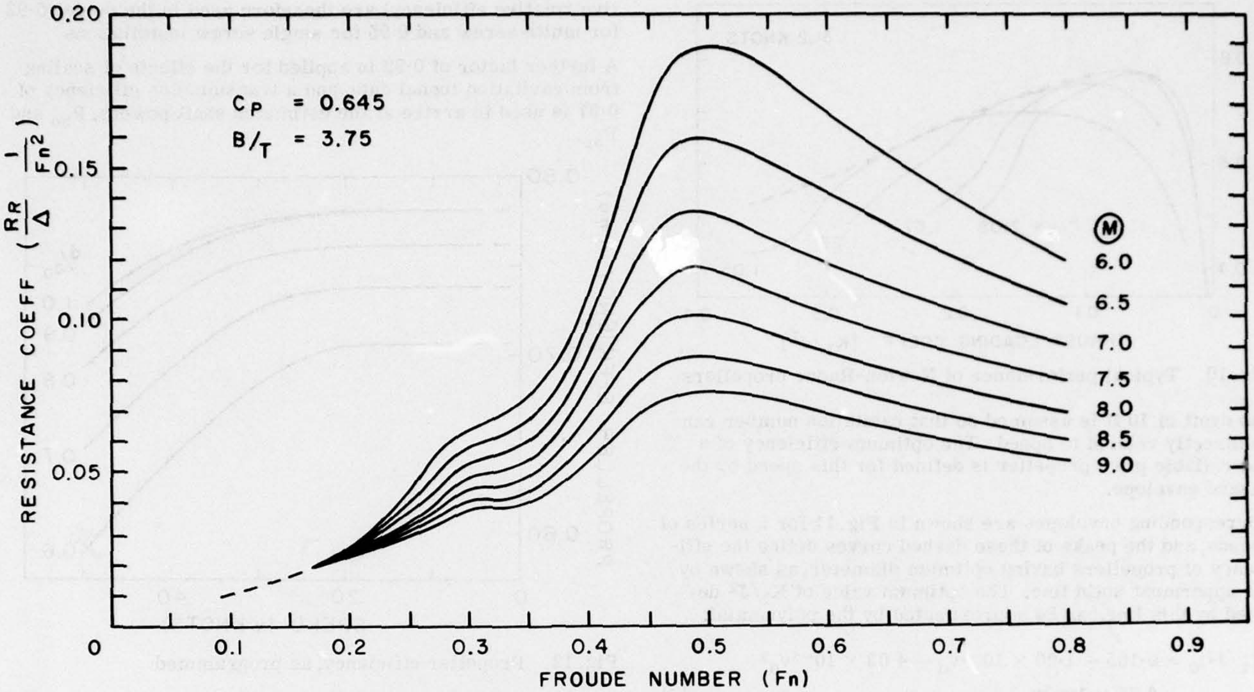

Fig. 7. Residuary resistance coefficient—Intermediate speed regime

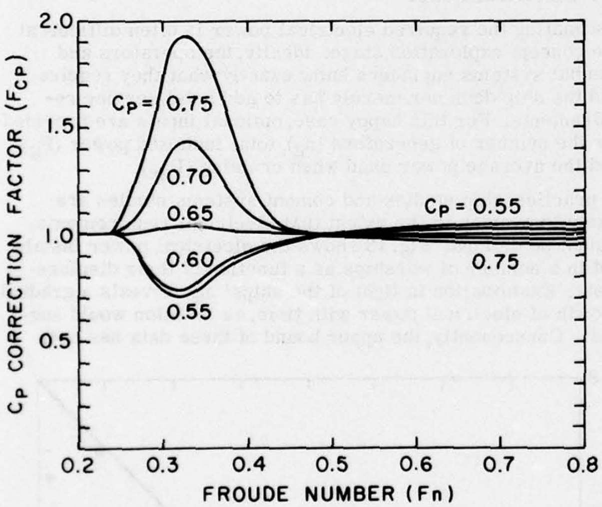

Fig. 8. Correction factor for C_P—Intermediate speed regime

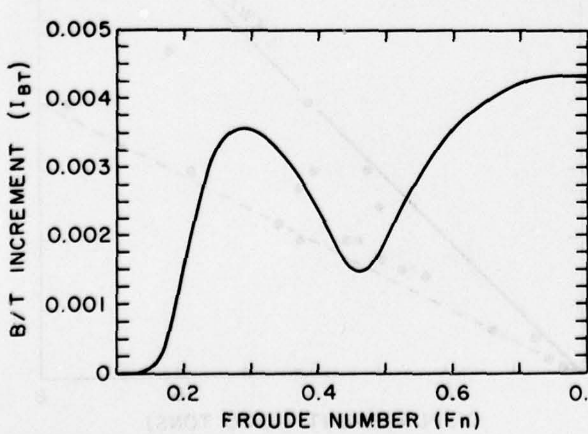

Fig. 9. Increment for B/T—Intermediate speed regime

4.2 Frictional Resistance and Allowance

The model automatically assigns a cruiser stern to ships in the low speed regime, and a transom stern in the other regimes, selecting the appropriate wetted surface correction. Frictional resistance is then simply estimated using the 1957 ITTC standard formulation, with a roughness allowance of 0·0004. Thus, the friction coefficient is:

$$C_F = 0{\cdot}075/(\log R_n - 2)^2 + 0{\cdot}0004 \qquad (13)$$

where R_n is the Reynolds number.

To the total of frictional and residuary resistance, a 20% allowance is added for appendages and service conditions, to arrive at the thrust required. These calculations are made at both design and cruise speeds, but with design speed governing the choice of regime, since this is effectively a choice of hull type.

4.3 Propeller Selection

Strictly, different speed regimes should also be used for propeller selection: no single type of propeller is ideal over the full range covered by the model. However, propellers based on the Newton-Rader series[9], which are certainly appropriate for the high speed regime, provide efficiencies only slightly less than other types at lower speeds. Thus, even though they would not be used in practice over so wide a range, Newton-Rader propellers do appear well suited to the purpose of the C.E. model.

The present model is restricted to warships powered by gas turbines, and assumes that controllable pitch propellers are fitted. Results from cavitation tunnel tests of a DREA designed C.P. propeller of Newton-Rader type[10] have been used for guidance in producing fair envelopes of the original fixed-pitch data.

The number of propellers installed is an optional input, with a default value of two.

4.4 Optimum Propeller Efficiency

Fig. 10 is a typical plot of propeller efficiency against thrust loading coefficient (defined as K_T/J^2) for a series of pitch-diameter ratios, at one hub cavitation number. An average

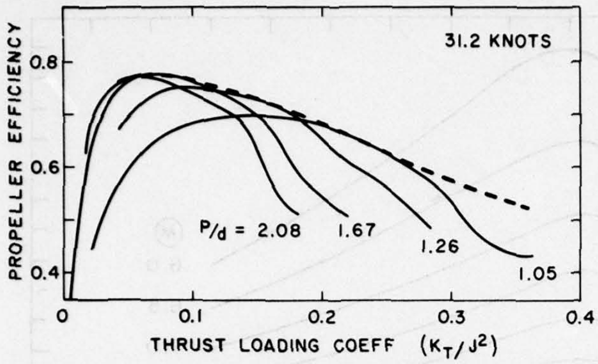

Fig. 10. Typical performance of Newton-Rader propellers

hub draft of 10 ft is assumed so that cavitation number can be directly related to speed. The optimum efficiency of a controllable pitch propeller is defined for this speed by the dashed envelope.

Corresponding envelopes are shown in Fig. 11 for a series of speeds, and the peaks of these dashed curves define the efficiency of propellers having optimum diameter, as shown by the uppermost solid line. The optimum value of K_T/J^2 defined by this line can be approximated by the polynomial:

$$(K_T/J^2)_o = 0{\cdot}105 - 1{\cdot}00 \times 10^{-4} v_d - 4{\cdot}03 \times 10^{-5} v_d^2 + 3{\cdot}76 \times 10^{-7} v_d^3 \qquad (14)$$

Hence, knowing the design speed and required thrust (per screw), the optimum propeller diameter (d_o) can be estimated.

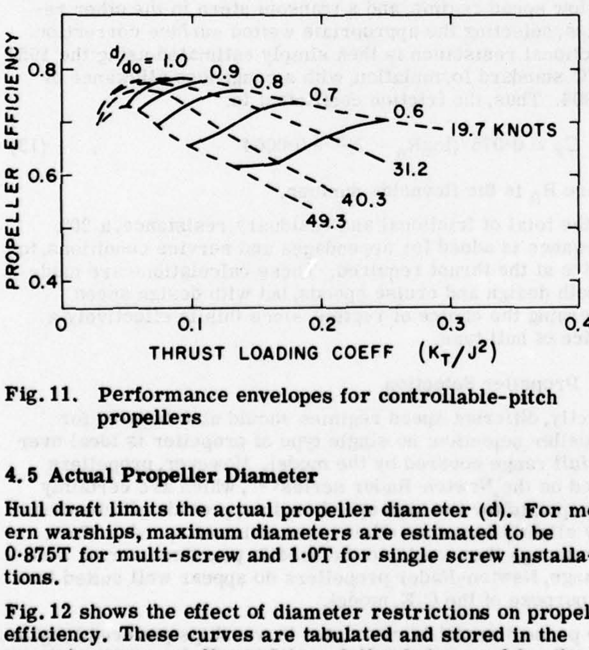

Fig. 11. Performance envelopes for controllable-pitch propellers

4.5 Actual Propeller Diameter

Hull draft limits the actual propeller diameter (d). For modern warships, maximum diameters are estimated to be 0·875T for multi-screw and 1·0T for single screw installations.

Fig. 12 shows the effect of diameter restrictions on propeller efficiency. These curves are tabulated and stored in the computer program, linear interpolation being used for the appropriate d/d_o ratio, to obtain the estimated propeller efficiency at design speed.

The same procedure is followed for the cruise condition. The actual diameter is now fixed, so there will be a new d/d_o value.

4.6 Other Efficiency Factors

Attempts to correlate data on hull-propeller interaction with primary hull parameters proved unsuccessful. With the data available, no reliable trends could be assigned to specific variables. Average values of hull efficiency (including relative rotative efficiency) are therefore used in the model; 0·92 for multi-screw and 0·95 for single screw installations.

A further factor of 0·92 is applied for the effects of scaling from cavitation tunnel data, and a transmission efficiency of 0·97 is used to arrive at the estimated shaft powers, P_{Sd} and P_{Se}.

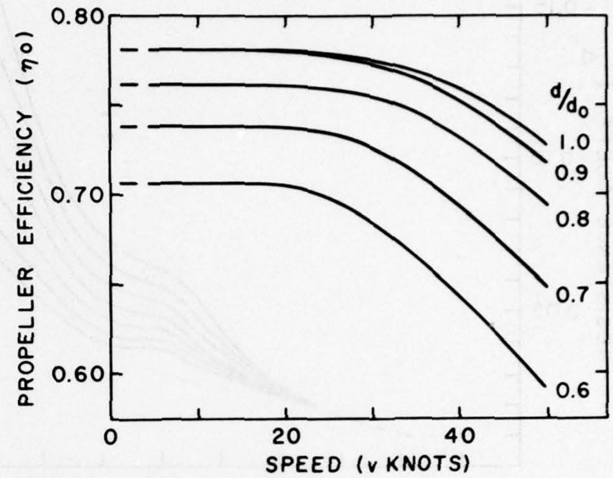

Fig. 12. Propeller efficiency, as programmed

4.7 Electrical Power

Estimating the required electrical power is often difficult at the concept exploration stage. Ideally, the operators and combat systems engineers know exactly what they require and the ship designer merely has to add hotel service requirements. For this happy case, optional inputs are provided for the number of generators (n_g), total installed power (P_g) and the average power used when cruising (P_{ge}).

In practice, ship studies and combat systems studies are likely to overlap to the extent that electrical requirements cannot be defined. Fig. 13 shows the electrical power installed in a number of warships as a function of their displacement. Examination in light of the ships' age reveals a gradual growth of electrical power with time, as intuition would suggest. Consequently, the upper bound of these data has been

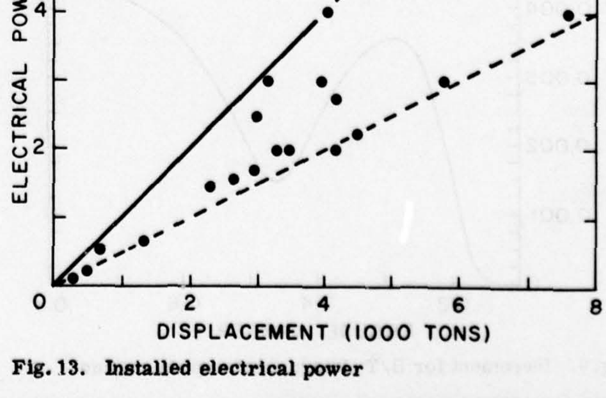

Fig. 13. Installed electrical power

chosen as the default value rather than the average. This is 1 KW per ton displacement. A consistent default value for the power used continuously under average cruise conditions is 25% of the installed power, and four generators are assumed to be fitted.

4.8 Specific Fuel Consumption

By the 1980s, an adequate choice of marine gas turbines should be available in the 3000-5000 SHP class, to provide a configuration of cruise engines well matched to the required power. A specific fuel consumption of 0·50 lb/SHP hour is a reasonable prediction for these small engines running near maximum continuous power, on a hot day and with appropriate intake and exhaust losses. A constant value of 0·50 lb/SHP hour is therefore assumed for powers up to 5000 SHP per propeller.

At higher powers, estimates have been based on the performance of the General Electric LM-2500 gas turbine, shown in Fig. 14. This engine would not be used for design powers lower than about 12 000 SHP per shaft, and a straight line approximation is assumed, as shown. This is,

$$f_S = 0{\cdot}525 - P_S/200{,}000 n_S \quad \text{lb/SHP hour} \tag{15}$$

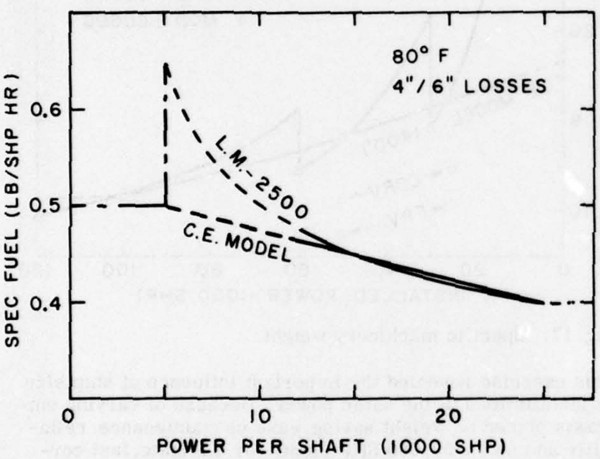

Fig. 14. Specific fuel consumption (propulsion)

Beyond 25,000 SHP per shaft, a constant value of 0·40 lb/SHP hr is taken as the likely practical limit.

This formulation assumes that engine configurations demanding 5000-12,000 SHP per shaft will either be avoided, or met with a new engine (such as a marine development of the Rolls Royce SPEY). For the latter case, the estimate is likely to remain valid.

Anticipated typical performance of 1980s gas turbine generator sets is shown in Fig. 15. The linear approximation assumed in the model is:

$$f_g = 1{\cdot}133 - P_g/3000 n_g \quad \text{lb/KW hour} \tag{16}$$

for powers up to 1000 KW per set, with a constant value of 0·80 lb/KW hr at higher powers.

An overall allowance of 5% is added for deterioration of both propulsion and generating machinery under service conditions.

4.9 Transport Effectiveness

For purposes of comparison, a useful performance parameter is 'specific power', defined by:

$$\Pi = R_{Td}/\Delta\eta_d = 0{\cdot}1454 P_{Sd}/\Delta v_d \tag{17}$$

(in units of horsepower, tons and knots.)

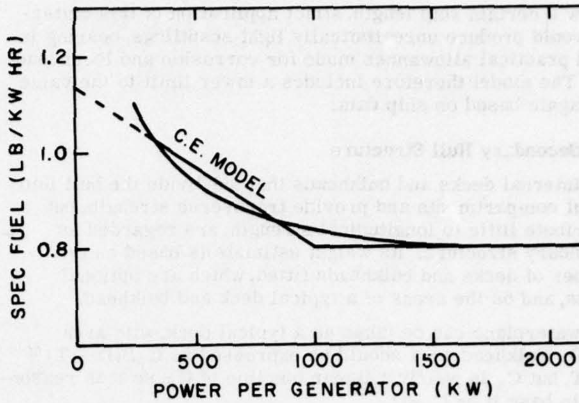

Fig. 15. Specific fuel consumption (electrical)

By combining this with the operational load ratio, W_u/Δ, an overall measure of the efficiency of the ship is obtained. This 'transport effectiveness' is:

$$e = W_u/\Delta\,\Pi = 6{\cdot}8876 W_u v_d/P_{Sd} \tag{18}$$

The word 'transport' is not to be interpreted literally, of course. Extended operations are not envisaged at maximum design speed.

5. WEIGHTS AND VOLUMES

5.1 Primary Hull Structure

The main contributors to longitudinal strength, namely the shell, framing, inner bottom, strength deck and their associated fastenings, are assumed to be distributed uniformly over the outside box of the ship, where they amount to a fictitious average thickness (t).

The underwater midship section is represented by a flat bottom trapezoidal section of appropriate waterline breadth, draft and section coefficient. For correct area, its bottom width is $B\,(2C_M - 1)$. Hence the total area of strength deck, bottom and sides is:

$$A_1 = C_W LB + C_W LB(2C_M - 1) + 2LD$$

Sheer and flare of topsides are ignored, assuming there is a compensating reduction of scantlings towards the ends. Then the weight of this primary structure is,

$$W_{h1} = 2wt(LBC_W C_M + LD) \tag{19}$$

where w is the density of the structural material, which is an optional input.

5.2 Longitudinal Strength Criterion

A formulation for the thickness, t, must ensure that a consistent standard of strength is adopted for all ships. The midships moment of inertia contributed by the strength deck and bottom is $2C_M Bt(D/2)^2$, so that section modulus is of the form, $C_M BDt$.

The applied moment is assumed to vary as ΔL and the permissible design stress as $\sigma\sqrt{L}$, where σ is the yield strength of the material, which is an optional input. (For merchant ships, variation with $L^{1/3}$ is normal, but the $\sqrt{L}$ law appears to fit available data for warships better up to lengths of 700 ft).

The fictitious average thickness is then defined in the form,

$$t = K_Z \Delta\sqrt{L}/\sigma C_M BD \tag{20}$$

where K_Z is a constant to be evaluated from data on existing ships.

Below a certain ship length, strict application of this criterion would produce unrealistically light scantlings, bearing in mind practical allowances made for corrosion and local loading. The model therefore includes a lower limit to the value of t, again based on ship data.

5.3 Secondary Hull Structure

The internal decks and bulkheads that subdivide the hull into useful compartments and provide transverse strength, but contribute little to longitudinal strength, are regarded as secondary structure. Its weight estimate is based on the number of decks and bulkheads fitted, which are optional inputs, and on the areas of a typical deck and bulkhead.

The waterplane can be taken as a typical deck, with area $C_W LB$. Bulkhead area should be expressed as $C_W B(D - T) + C_B BT$, but C_W is nearly a linear function of C_B, so it is reasonable to base it on $C_W BD$.

When analysed in this form, it appears that the effective thickness of deck structure is approximately half that of bulkhead structure, and the total weight of secondary structure can be estimated in the form:

$$W_{h2} = wt_2 LBC_W(n_d + 2n_b D/L) \qquad (21)$$

where t_2 is a constant evaluated from data on existing ships.

5.4 Superstructure

The variety of shapes of warship superstructures defy a simple rational analysis. However, if superstructure weight is based on its length, L_S, and on the sum of the ship's breadth and depth, i.e.,

$$W_{h3} = wt_3 \; L_S(B + D) \qquad (22)$$

then t_3 values are found to be scattered close to the value of t_2, which is convenient.

In case the length of superstructure remains undefined at the concept exploration stage, a default value of 0·5L is provided. In practice, the designer will probably use L_S to adjust the model to his own first guess at superstructure weight.

5.5 Total Hull Structure

In addition to the three components discussed above, an allowance is made for foundations and miscellaneous structure, as a small constant percentage of the displacement. Fig. 16 shows some results of applying this method. Hull structure weight as a fraction of displacement is plotted against displacement, the open points being ship data and the solid points being the estimates. Errors vary from +9% to −12%, without pattern, and most are less than 7%. It is encouraging that one cannot detect from the errors which were the ships used to derive the K_Z and t_2 values, and which were not.

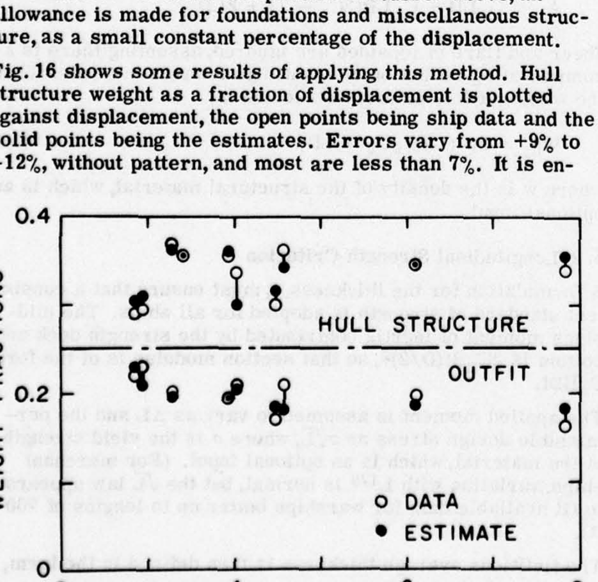

Fig. 16. Accuracy of hull structure and outfit weight estimates

5.6 Machinery Weight

The most serious shortcoming of the data base for this model is the weight and volume of gas turbine power plants. Within navies willing to provide data, there are too few all gas turbine ships. Moreover, some engineers look scathingly on the early examples, claiming them to have 'modified steam plants' that fail to exploit the potential advantages of gas turbines.

An attempt was originally made to conceive hypothetical installations of 30,000, 60,000 and 120,000 SHP in COGAG configuration, to provide additional data. The 'zig-zag' line in Fig. 17 shows the specific machinery weight that results from using these (MOD 1) installations at intermediate powers. In practice, their use caused severe design problems and, although this is symptomatic of the real situation in which ship size has to be matched to a limited choice of installations, the line in Fig. 17 is obviously too simplistic.

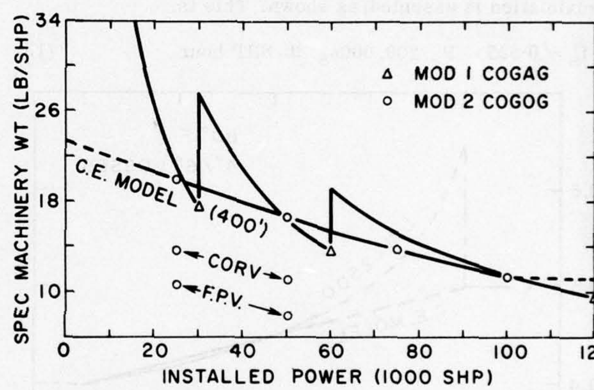

Fig. 17. Specific machinery weight

This exercise revealed the important influence of ship size on installations of the same power. Because of varying emphasis placed on weight saving, ease of maintenance, reliability and so on, 50,000 SHP plants for a frigate, fast corvette and hydrofoil would differ significantly. As a further guide, COGOG installations were schemed for various powers and ship types, and these MOD 2 studies are also indicated in Fig. 17. This work suggested that specific weights would be reasonably predicted by a $\sqrt{L}$ variation with ship size.

It was eventually decided that the selection of a realistic installation lay beyond the scope of concept exploration, and that it would be better to use a continuous curve, or 'rubber engines', for the C.E. model. The continuous line shown in Fig. 17 shows the specific machinery weight, w_m lb/SHP, selected for 400 ft ships in the C.E. model.

Lacking adequate factual data, the trend of this estimate relative to steam plants and to other gas turbine design studies is of interest. Fig. 18 presents machinery weight data plotted against installed power × $\sqrt{\text{length}}$. The dashed lines show trends of existing steam plants and gas turbine studies, tending to confirm the $\sqrt{\text{length}}$ variation. C.E. model estimates fall close to the study trend line at higher powers and appear a little conservative at the low end. However, they do imply a significant weight reduction compared with two of the existing gas turbine plants.

5.7 Electrical Plant, Auxiliary Systems and Outfit

This category covers a large miscellany of items, few of which can be treated rigorously. The approach has been to identify and group those weights that can be expected to depend primarily on:

(a) Overall ship size, represented by displacement, Δ.

(b) Upper deck area, represented by the product LB.

(c) Ships complement, N. (see Section 5.15)

(d) Installed electrical power, P_g.

The estimate is made in the simple linear form:

$$W_o = a\Delta + bLB + cN + dP_g \quad (23)$$

where the coefficients a, b, c, and d are evaluated from available ship data. Fig. 16 shows the results of applying this estimate, in the same format used for hull structure weight. Errors vary from +13% to −14%, and most are less than 9%.

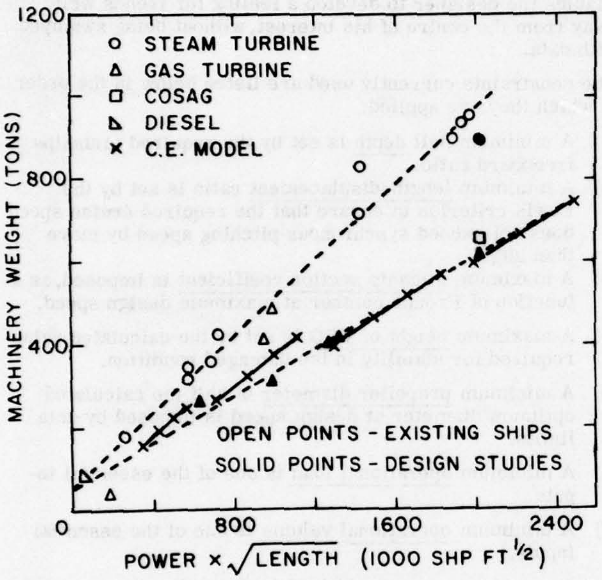

Fig. 18. Comparison of machinery weights

5.8 Disposable Weight

A similar approach is used for those variable loads that are not considered part of the operational load; items such as crew and effects, stores and provisions, fresh water and lubricating oil. The estimate takes the form,

$$W_d = e\Delta + fN + gW_f \quad (24)$$

where W_f is the fuel weight. In this case, the coefficients e, f and g are based on allowances customarily made for these items by Canadian Forces. Because logistic practices differ, an analysis of data from ships of different nations is impractical.

5.9 Extra Basic Weight

For most ships, the sum of all the foregoing components will be the complete basic ship weight. Since estimates have been based on data for existing ships, no 'design margin' is appropriate.

However, the designer may wish to add a further margin for some purposes. There may also be special features for which no allowance has been made, such as water in stabilising tanks, or armour added to the normal structure. Optional inputs are therefore provided for an 'extra basic weight' and its VCG.

5.10 Fuel Weight

The weight of fuel is calculated directly from the required endurance at cruise speed, using estimated cruise power and overall specific fuel consumption. A 5% allowance is made for trapped fuel.

5.11 Operational Weight

The difference between the displacement and the sum of all the foregoing weights is the available operational weight, W_u. This is the final figure that is compared with the minimum acceptable operational load specified by the designer in the SEARCH mode.

5.12 Centres of Gravity

The C.E. model is concerned only with vertical moments. For each of the weight components described above, a VCG is also estimated from data for existing ships, as a fraction of the hull depth in most cases. The VCG of the operational weight is an optional input, enabling the designer to override the default value of 0·7D if the fighting equipment to be carried demands an abnormal configuration.

KG can then be calculated and compared with the maximum KG_O allowable for stability.

5.13 Total Volume

The total available volume, V_T, is estimated in three parts; displacement volume, above water hull and superstructure. The above water hull volume is based on waterplane area, freeboard and a factor to account for sheer and topside flare:

$$V_{Ha} = 1{\cdot}15\, C_W\, LB(D - T) \quad (25)$$

Superstructure volumes of modern warships vary so widely that no rational estimating basis appears possible. Consequently, this has been made an optional input, and the default value of $0{\cdot}25\, V_T$ is simply based on the Canadian Forces' most recent class of DDH.

5.14 Machinery Volume

Fig. 19 presents available data on machinery volume as a function of displacement, which appears to be a better basis than any function of power. This is probably because machinery spaces usually extend across the full breadth of small warships regardless of engine size. Similarly, the height of the machinery space extends to the most convenient deck level, while intakes, exhaust, access routes and shaft tunnels are also largely governed by ship dimensions.

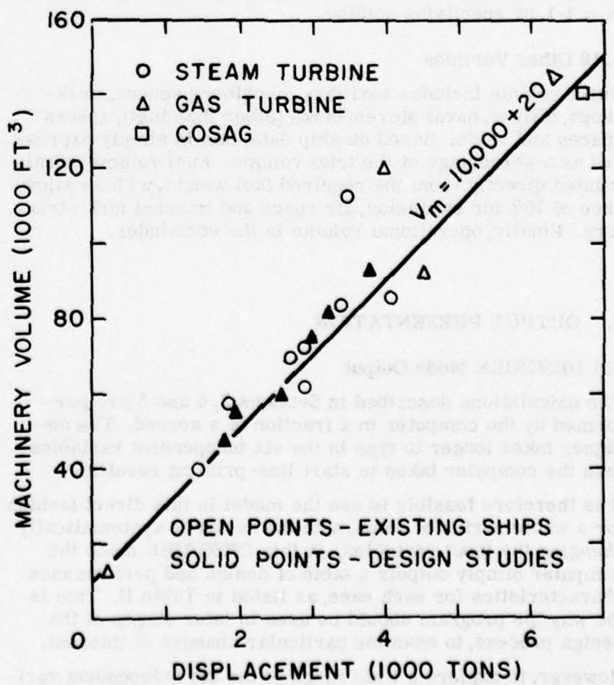

Fig. 19. Comparison of machinery volumes

For these reasons one cannot expect a reduction of volume commensurate with the weight saving predicted for future all gas turbine installations. Pending better data, the trend line shown in Fig. 19 has been accepted for the C.E. model.

5.15 Personnel Volume

The volume of spaces devoted to crew living, sustenance and recreation is based on complement, using an average space per man obtained from data on existing ships. Fig. 20 shows complement plotted as a function of displacement, the curves corresponding to a 2/3 power law:

$$N = m\Delta^{2/3} \quad (26)$$

Ships operating and maintained from a home port tend to lie along the lower line ($m = 0{\cdot}9$), while those designed for self-maintenance on a world-wide basis lie at the top ($m = 1{\cdot}3$). The value of m has been made an optional input, called 'maintenance factor'.

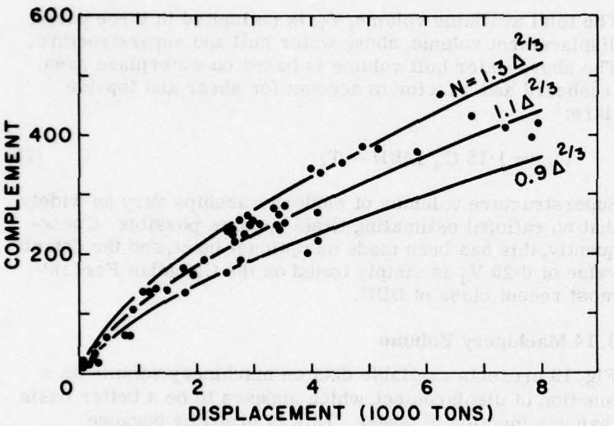

Fig. 20. Ship's complement

The designer thus has three options. He can specify a desired complement, in which case m has no significance. He can specify a value of m, or he can accept the default value, $m = 1{\cdot}1$, by specifying nothing.

5.16 Other Volumes

Outfit volume includes auxiliary machinery spaces, workshops, offices, naval stores, tanks (other than fuel), access spaces and voids. Based on ship data, this is simply expressed as a percentage of the total volume. Fuel volume is calculated directly from the required fuel weight, with an allowance of 10% for expansion, air space and internal tank structure. Finally, operational volume is the remainder.

6. OUTPUT PRESENTATION

6.1 DESCRIBE Mode Output

The calculations described in Sections 3, 4 and 5 are performed by the computer in a fraction of a second. The designer takes longer to type in the six independent variables than the computer takes to start line-printing results.

It is therefore feasible to use the model in this direct fashion for a whole series of ships, with the designer systematically changing the input variables. In this DESCRIBE mode the computer simply outputs a table of design and performance characteristics for each case, as listed in Table II. This is the way the program should be used in later stages of the design process, to examine particular changes of interest.

However, to explore a wide range of the six independent variables in an initial search, thousands of possible cases must be examined. The computation time might be reasonable enough, but assessing the results would be an impractical task.

6.2 SEARCH Constraints

Most of the possible cases will not lead to satisfactory ship designs. A system of constraints is used in the SEARCH mode to reject impractical cases at the earliest opportunity in the calculations, thus reducing the output to reasonable proportions.

The model maintains a count of the number of violations of each constraint, and outputs these numbers along with each 'block' of acceptable ships, as described in Section 6.3. This enables the designer to develop a feeling for trends well away from the centre of his interest, without being swamped with data.

The constraints currently used are listed below in the order in which they are applied:

(1) A minimum hull depth is set by the required midships freeboard ratio.

(2) A minimum length-displacement ratio is set by the Lewis criterion to ensure that the required cruise speed does not exceed synchronous pitching speed by more than 20%.

(3) A maximum midship section coefficient is imposed, as a function of Froude number at maximum design speed.

(4) A maximum height of VCG is set by the calculated value required for stability in the damaged condition.

(5) A minimum propeller diameter of half the calculated optimum diameter at design speed is imposed by data limits.

(6) A minimum operational load is one of the essential inputs.

(7) A minimum operational volume is one of the essential inputs.

(8) A maximum operational load is set by the chosen gate factor.

(9) A maximum operational volume is set by the chosen gate factor.

6.3 SEARCH Mode Output

The format of the SEARCH mode output is illustrated in Fig. 21. Block 'A' presents the operational objectives governing the search. Block 'B' shows the limits and step sizes of the six independent variables on which the search has operated.

The central part of the output presents data divided into major blocks, 'C', each corresponding to a particular ship-length and arranged in order of increasing length. These are subdivided into minor blocks, 'D' corresponding to decreasing Ⓜ values. Thus all ships presented within a 'D' block will have the same displacement, and will comprise all acceptable combinations of the four remaining variables, C_P, C_B, B/T and L/D.

For each acceptable ship found, a single line of data is printed in the 'D' block, containing those key characteristics of the design that are marked with an asterisk in Table II. In addition, the final line of each 'D' block states the displacement and Ⓜ value for the block, together with counts of the number of violations caused by each of the nine constraints. This last line is, of course, the only data printed if no acceptable ships are found at that displacement, and the violation counts will suggest why none were acceptable.

On completion of the calculations, the best ship of each displacement or 'D' block is selected according to the optimisation criterion chosen. Full lists of ship characteristics are then output in the 'E' blocks for up to 18 of these best ships, ordered by the value of the optimisation criterion. Thus each numbered column in Fig. 21 contains the data listed in Table II.

With this format, the designer has, in the 'D' blocks, salient

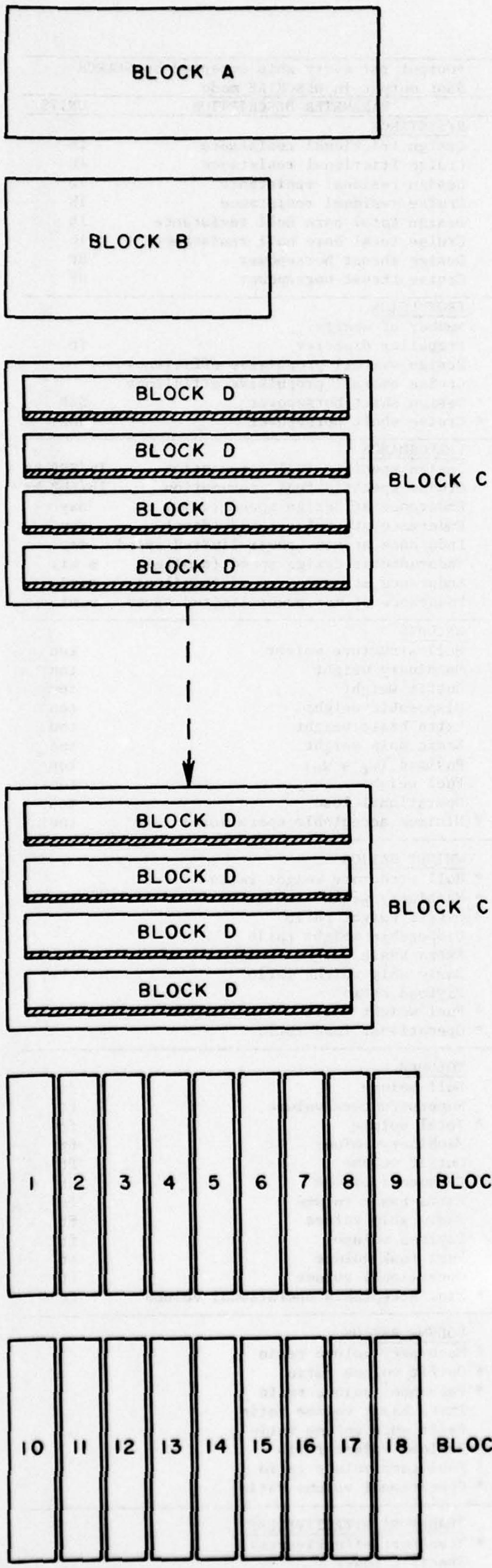

Fig. 21. Format of SEARCH mode output

features of a sufficient number of ships to discern meaningful trends and, in the 'E' blocks, has detailed information on the few likely to be of greatest interest. Should he wish to obtain full data on any other ships in the 'D' blocks, he merely has to re-enter their independent variables in the DESCRIBE mode.

7. CONCLUDING REMARKS

7.1 Applications

In a typical initial search, the model was used to examine 8 ship-lengths, 8 values of Ⓜ and 6 values of each of the other independent variables. Hence the computer examined 82, 944 possible combinations, found that 278 represented acceptable ships and provided key design characteristics for each. It then selected the 18 'best' ships and presented full (Table II) descriptions of these. It did this in 8 minutes. Manually checking one possible combination through the algorithm with a desk calculator took an experienced designer a little more than a day.

Having conducted an initial search over a wide range of variables, the designer might then narrow his search to obtain more reliable trends in the region of interest. Alternatively, if he had a good basis ship available to him within this region, he might prefer to go directly to a systematic series of variations on the dimensions of that ship, using the DESCRIBE mode.

Optional inputs could then be set to match the basis ship, and by choosing one combination of dimensions to duplicate that ship, the designer would have an immediate check on the accuracy of the model applied to his case. Adjustments could be made to appropriate empirical constants to provide a better fit. In this way the function of the model can change from concept exploration to a reference standard with which the effect of subsequent changes to the design can be rapidly assessed.

Although the model has been tailored to its primary role as a versatile tool for the practising designer, it can also be used for parametric studies of value to operational research into future ship requirements. Such studies can give general guidance in advance of actual design work on the likely tradeoffs between payload, range and speed. They could estimate the penalty in ship size likely to be involved in asking for an extra 5 knots, or 50 tons more military load. Perhaps after enough of these studies have been done, the designers may even realise their dream of being given an operational requirement that is not impossible to meet.

The flexibility of the model makes it impossible to assess its accuracy in any absolute sense. It has predicted the characteristics of existing ships within a few percent, but such tests are not objective. If enough data are available on a ship for it to be a suitable test case, that ship has already been used in the data base of the model. Such is the scarcity of data.

Indeed, lack of data is the major limitation, particularly in regard to gas turbine powered ships. Fortunately, the computer program is easily treated as a 'live document', with empirical constants and other parts of the algorithm updated as new data become available.

7.2 Future Additions

In matters of principle, the major shortcoming of the model is its inadequate treatment of seakeeping. No longer should the warship designer be regarding maximum speed in calm water as one of his major operational objectives. The ability to maintain speed under all sea conditions is a more important criterion, and recent advances in seakeeping theory now introduce the possibility of designing to achieve a specified speed in a specified sea state. This was appreciated when the authors undertook to develop the C.E. model. However, they also recognized that a method of designing for optimum performance in rough water would take significantly longer

TABLE II. OUTPUT PARAMETERS

*Output for every ship accepted by SEARCH
#Not output in DESCRIBE mode

NOTATION	PARAMETER DESCRIPTION	UNITS
	DIMENSIONS	
Δ	* Displacement	ton
L	* Waterline length	ft
B	Breadth	ft
T	Draft	ft
D	Depth	ft
F	Freeboard	ft
S	Wetted surface area	ft^2
$\nabla^{1/3}$	Displacement volume to 1/3 power	ft
$\nabla^{2/3}$	Displacement volume to 2/3 power	ft^2
∇	Displacement volume	ft^3
	FORM RATIOS	
Ⓜ	* Length-displacement ratio - $L/\nabla^{1/3}$	
L/B	Length-breadth ratio	
L/D	* Length-depth ratio	
B/T	* Breadth-draft ratio	
Ⓢ	Wetted surface area ratio	
Δ_L	Displacement length-ratio - $\Delta/(0{\cdot}01L)^3$	
	FORM COEFFICIENTS	
C_B	* Block coefficient	
C_P	* Prismatic coefficient	
C_M	Midship section coefficient	
C_W	Waterplane area coefficient	
C_{VP}	Vertical prismatic coefficient	
C_{It}	Inertia coefficient of waterplane	
C_V	Volumetric coefficient	
	MISCELLANEOUS	
D_o	Minimum depth	ft
F_o	Minimum allowable freeboard amidships	ft
Ⓜ$_o$	# Minimum length-displacement ratio	
H_W	Significant wave height	ft
L_S	Superstructure length	ft
P_g	Installed electrical power	KW
P_{ge}	Cruise electrical power	KW
n_g	Number of electrical generators	
N	Complement (maximum accommodation)	
m	Maintenance factor	
	STRUCTURE	
c	Compartment standard of flooding	
σ	Yield stress of primary hull material	ton/in^2
w	Density of primary hull material	ton/ft^3
n_d	Number of decks below upper deck	
n_b	Number of main watertight bulkheads	
	STABILITY	
z_{uo}	VCG of operational load	ft
F_1	Minimum freeboard for flooding	ft
KB	Keel to centre of buoyancy	ft
BM	Metacentric radius	ft
GM_o	Loss of GM due to flooding	ft
KG_o	Maximum acceptable value of KG	ft
KG	Keel to centre of gravity	ft
GM	* Metacentric height	ft
GM_f	Metacentric height, liquid corrected	ft
T_ϕ	Roll period	sec
	SPEEDS	
v_d	Maximum continuous calm water speed	kt
v_e	Cruise speed for required endurance	kt
v_R	Synchronous pitching speed	kt
v_W	Max. power limited speed in waves	kt
$v_d/\sqrt{L}$	Design speed-length ratio	$kt/ft^{1/2}$
$v_e/\sqrt{L}$	Cruise speed-length ratio	$kt/ft^{1/2}$
$v_R/\sqrt{L}$	Synchronous speed-length ratio	$kt/ft^{1/2}$
$v_W/\sqrt{L}$	Max. power limited speed-length ratio	$kt/ft^{1/2}$
F_{nd}	Design Froude number	
F_{ne}	Cruise Froude number	
F_{nR}	Synchronous Froude number	
F_{nW}	Max. power limited Froude number	
v_e/v_R	* Cruise-synchronous speed ratio	
v_W/vd	Max. power limited design speed ratio	

*Output for every ship accepted by SEARCH
#Not output in DESCRIBE mode

NOTATION	PARAMETER DESCRIPTION	UNITS
	RESISTANCE	
R_{Fd}	Design frictional resistance	lb
R_{Fe}	Cruise frictional resistance	lb
R_{Rd}	Design residual resistance	lb
R_{Ee}	Cruise residual resistance	lb
R_{Td}	Design total bare hull resistance	lb
R_{Te}	Cruise total bare hull resistance	lb
P_{Td}	Design thrust horsepower	HP
P_{Te}	Cruise thrust horsepower	HP
	PROPULSION	
n_s	Number of shafts	
d	Propeller diameter	ft
η_d	Design overall propulsive efficiency	
η_e	Cruise overall propulsive efficiency	
P_{Sd}	* Design shaft horsepower	SHP
P_{Se}	* Cruise shaft horsepower	SHP
	PERFORMANCE	
f_d	Design specific fuel consumption	lb/SHP hr
f_e	Cruise specific fuel consumption	lb/SHP hr
–	Endurance at design speed (days)	day
–	Endurance at cruise speed (days)	day
–	Endurance at max. power limited speed	day
E_d	Endurance at design speed (n.miles)	n.mi.
E	Endurance at cruise speed (n.miles)	n.mi.
E_W	Endurance at max.power limited speed	n.mi.
	WEIGHTS	
W_h	Hull structure weight	ton
W_m	Machinery weight	ton
W_o	Outfit weight	ton
W_d	Disposable weight	ton
W_x	Extra basic weight	ton
W_b	Basic ship weight	ton
W_p	*Payload* $(W_f + W_u)$	*ton*
W_f	Fuel weight	ton
W_u	Operational load	ton
W_{uo}	# Minimum acceptable operational load	ton
	WEIGHT RATIOS	
W_h/Δ	* Hull structure weight ratio	
W_m/Δ	* Machinery weight ratio	
W_o/Δ	* Outfit weight ratio	
W_d/Δ	Disposable weight ratio	
W_x/Δ	Extra basic weight ratio	
W_b/Δ	Basic ship weight ratio	
W_p/Δ	Payload ratio	
W_f/Δ	* Fuel weight ratio	
W_u/Δ	* Operational load ratio	
	VOLUMES	
V_H	Hull volume	ft^3
V_S	Superstructure volume	ft^3
V_T	* Total volume	ft^3
V_m	Machinery volume	ft^3
V_o	Outfit volume	ft^3
V_n	Personnel volume	ft^3
V_x	Extra basic volume	ft^3
V_b	Basic ship volume	ft^3
V_p	Payload volume	ft^3
V_f	Fuel tank volume	ft^3
V_u	Operational volume	ft^3
V_{uo}	* Min. acceptable operational volume	ft^3
	VOLUME RATIOS	
V_m/V_T	* Machinery volume ratio	
V_o/V_T	* Outfit volume ratio	
V_n/V_T	* Personnel volume ratio	
V_x/V_T	Extra basic volume ratio	
V_b/V_T	Basic ship volume ratio	
V_p/V_T	Payload volume ratio	
V_f/V_T	* Fuel tank volume ratio	
V_u/V_T	* Operational volume ratio	
	TRANSPORT EFFECTIVENESS	
e	* Transport effectiveness	
Π	Specific power	

to develop, and be more complex. The compromise was the present model, together with a program of research towards that more ambitious goal.

Another desirable addition would be a costing algorithm enabling the search to be for ships of minimum cost instead of minimum size. In terms of initial acquisition costs, the differences are likely to be small, and have been judged not worth the risk of introducing misleading sources of error through the unreliability of cost data now available. Operating costs would also be involved, the true criterion being the overall life cycle cost of the ship. Here, despite the rising price of fuel, manning costs overshadow all others, and if the model relies on the kind of data shown in Fig. 20, size dependence again dominates.

It is therefore questionable whether a costing model would provide better guidance until a more rational basis is developed for manning. With increased automation and decreased maintenance through 'repair by replacement' policies, the technology exists to refute the statistics of Fig. 20.

In conclusion, the present concept exploration model should be viewed as a basic tool capable of refinement and increased versatility. How far it is desirable to expand the model in the quest for greater accuracy depends on the use contemplated for it, relative to more extensive computer based methods developed for subsequent phases of the design process. Convenience and flexibility of use are more likely targets for improvement than expansion, beyond the introduction of seakeeping criteria currently being developed.

8. ACKNOWLEDGMENTS

A vigorous dialogue between model developer and would-be user has been an essential factor in the conduct of this work. Many officers at DREA and in the Directorate of Maritime Engineering and Maintenance have contributed their ideas and their time. The authors would particularly wish to thank Cdr C. D. Roushorn, Head of the Preliminary Design Section, DMEM, and Mr I. F. Glen (on exchange duty from the RCNC) for their focal role in sponsoring this project.

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DISCUSSION

Cdr C. D. Roushorn, CD, BSc, SM, NavE, PEng (read by Lt Cdr D. C. Wright): The authors have presented this paper on concept exploration in the clear and concise style that is typical of their work. My congratulations to them both.

I would like to take this opportunity to emphasise two points which the authors have touched upon in the paper. First, the concept exploration model is intended to assist the warship designer in three specific areas. These are:

(a) to develop concept design studies prior to the origin of specific staff requirements,

(b) to provide a rational set of warship data suitable for operations research analysis, and

(c) to establish a start zone for the preliminary design process.

Of these three areas, the concept exploration model has been applied in practical terms to a series of concept design studies during 1975.

Second, the user must be an experienced warship designer who is aware of both the limitations and the merits of the concept exploration model. He must interpret his input data and the output results with sound judgement. Only when the user has developed a confidence in the model should he attempt to apply it in a practical sense.

Lt Cdr D. C. Wight: I would now like to take this opportunity to outline briefly how we in Project Definition have used the concept exploration model.

Prior to practical usage, the model was run to compare its output parameters with those generated using our normal and more conservative design study methodology. Discrepancies were, for most outputs, within 10%. This is thought to be well within the limits of acceptability because, in these preliminary areas of ship design, the user is mainly interested in relative outputs and ship parameter trends. It is, of course, imperative that the model produces feasible ships so that the designer can meaningfully predict trends from parameter variations.

Our first practical usage of the model was to determine the effect, on the ship as a whole, of varying the ship's complement. The model enabled us to complete within one day what previously would have been a most tedious task.

A recent requirement for our Project Definition Section was to provide for staff a family of ships, each member of the family carrying a specific operational load. We then wanted to explore the results of varying space design margins for each of these ships. The concept exploration model is particularly well suited to this type of task. The 'search mode' was used to permit the designer to select what he regarded as a 'best' ship for each operational load requirement. The 'describe mode' was then used to produce the variations of these 'best' ships to cater for changes in space margin philosophy.

One of the points that the authors make in Section 1.1 is that if the operational requirements for a new ship differ radically from any previous ship, the designer will have a problem in selecting an appropriate basis ship. In these recent design studies, one operational load package contained a payload item which required a large under-deck space for relatively low density requipment. It was most interesting to note that

what appeared to be 'best' ships to carry this operational load differed significantly from the 'best' ships to carry the other operational loads. Unfortunately, from a concept exploration point of view, staff has now dropped this operational load requirement so that this particular ship concept will not be further developed.

In conclusion, I would like to congratulate the authors not only on presenting a fine paper, but also on providing us in Project Definition with a most versatile design tool.

Mr D. G. M. Watson, B.Sc. (Fellow): The subject of this paper—the preliminary design of ships—is one that I have always found absorbingly interesting. It is a subject on which relatively little has been written for ships generally, and even less for warships—so this paper is doubly welcome.

1. 1.

The authors get off to a good start with a sensible centripetal spiral which shows every sign of providing a satisfactory route to a suitable design—unlike many other design spirals I have seen whose centrifugal construction seems expressly constructed to enable them to fly off at a tangent. I greatly regret I have not had time to put to the test the many approximate formulae which the authors quote and cannot yet comment on these as I would have liked. The logic on which most are based, however, appears sound and I look forward to trying them out.

1. 2.

In Section 1. 2 and later in Section 7. 2 the authors refer to costing. In Section 2 they say 'Experience has shown that size and acquisition cost are closely related and even a warship's complement (the largest component of operating cost) is statistically related to ship size'.

I do not doubt the truth of these statements as applied to existing ships, but I am convinced that neither need be true if steps were taken to control an 'Admiralty' law (and I hope that now there is no longer an Admiralty I can use this name without offending my friends in MoD(N)) which states:

(i) Weight will always be added to take up any margin of weight allowed in a design—and will often cause substantial increases in the originally designed displacement and generally a reduction in the intended metacentric height.

(ii) All available space will be filled to an unreasonable density with equipment.

If the original design contemplated a lower density of equipment than normal then the rule which says 'cost is proportional to size' would not apply, and indeed it is possible that if two designs were prepared to carry identical equipment, it would be found that the larger ship was cheaper to construct and cheaper to operate.

The strength of character required in a project manager to defeat the 'Admiralty' law would be very considerable but I believe it could be done and deprecate therefore the assumption implied in concept exploration that the minimum size of ship is the ultimative objective.

2. 2.

I find myself questioning the choice of the independent variables, and would like the authors' views on why these were selected. My own choice would have been:

(1) L

(2) Ⓜ $(L/\nabla^{1/3})$

(3) L/B

(4) B/D

(5) T/D

(6) C_p

My reasons for preferring these relationships are:

(3) L/B—is fundamental to powering and manoeuvrability.

(4) B/D—is fundamental to stability.

(5) T/D—is fundamental to seakeeping.

By comparison, in my view, B/T and L/D are relatively meaningless relationships for the type of ship being considered. With my choice of independent variables I have had to omit C_b which I am reluctant to lose, but the choice lies between C_b and Ⓜ and I can see advantages for warships in particular in retaining Ⓜ.

2. 3. Operational Objectives

I would like to suggest an addition to the program with the endurance E being made up of two factors of a distance E_d to be covered at design speed with maximum continuous power plus a distance E_c to be covered at cruise speed and power.

2. 4. Operational Inputs

The concept of default values is well thought out and will greatly increase the usefulness of the program. The same remarks apply to the idea of gate values.

3. 0.

I must now skip the formula given in 3. 1, 3. 2, 3. 3, 3. 4, 3. 5 and turn to 3. 6 and 3. 7 and ask whether the program has an option for ships with side to side bridge erections. An erection of this sort would alter the freeboard amidships very significantly and would also modify the ratio V_S/V_H referred to later. For many smaller warships the use of a bridge superstructure appears to have design advantages.

3. 10. Loss of Speed in Waves

Is equation(12) correctly reproduced? It would appear to indicate that for a given wave height/ship length ratio the percentage fall off in speed is greater for a small Froude number than it is for a large number. There also appear to be possibilities of v_w/v_d exceeding unity. I would not have expected this and would be glad to have an explanation, which may lie in the limits within which the equation is applicable.

4. 0. Performance Estimation

There appears to be a wealth of data here which I intend to explore because, as the authors say, data is extremely scarce in this region. I wonder if the authors would care to comment on why they have worked with residuary resistance coefficients in preference to Ⓒ.

4. 3.

In 4. 3 the authors state that 20% is added for appendages and service conditions—would it be correct to add of 'hull finish'? I presume this is still a power estimate for ideal trial conditions.

Are all the ships considered twin screw? For a single screw option the addition for appendages seems very high.

4. 4 Propellers

I wonder whether the best treatment has been adopted in this section. It seems to me rather a round-about approach to consider the efficiency and diameter of the optimum propeller and then obtain the efficiency of the actual propeller by using a d/d_o ratio. Why not calculate the maximum possible diameter of propeller first and enter the propeller efficiency evaluation from this point. If the evaluation of the other efficiency factors has proved unsatisfactory there might be a lot to be said for making a direct estimation of the QPC from a variant of Emerson's formula. Emerson modestly claims his formula is for slow speed propellers on single screw merchant ships, but I have found it to be surprisingly accurate for a wide range of ship types, sizes and propeller revs.

4. 7. Electrical Power

Agreed, always a difficult problem. The authors' suggestion appears reasonable.

4. 8. Specific Fuel Consumption

No comment—except why is no consideration given to the use of diesels for cruise engines and for the generators?

4. 9.

Is transport effectiveness really a useful parameter? I would have thought the values would vary widely and not be particularly suitable for correlation purposes.

5. 1. Primary Structure Weight

I like the numeral developed for this and believe this could be a good estimating method to use.

This applies also to the derivation of the fictitious average thickness. The secondary hull structure formula also seems to me to have a very good basis.

I am less happy about the treatment of superstructure and suggest this should be based on its volume—a theme to which I will return when talking about volume and stability.

5. 6. Machinery Weight

My first thoughts on this are that at least two more triggers should be added to the program. One to indicate the use of an 'and' configuration COGAG, or an 'or' configuration COGOG and one to indicate that diesels may be used for the cruise engines CODAG or CODOG.

The second point I would like to make relates to the desirability of splitting machinery weight into at least two components—the main propulsion machinery and the auxiliaries. The weight for the former being read directly against power whilst that for the latter would be better related to ship dimensions in some way.

5. 9. Extra Basic Weight

I am unhappy with the statement that 'since estimates are based on data from existing ships no design margin is appropriate'. I have always tried to base weight estimates to some degree on existing ships, but would never have thought it wise to dispense with a margin on this account.

5. 12. Centres of Gravity

5. 13. Total Volume

I would like to link these two sub-sections together. I am not happy about the method of arriving at the VCG on the basis of a percentage of the depth without any apparent cognizance being taken of the percentage of the total volume which is provided by the erections. It is possible to have two ships which meet the same stability criterion, one with a high depth to the weather deck and a low percentage of erections, and the other with a low depth to the weather deck and a high percentage of erections. It seems to me that it might be possible to eliminate many unsatisfactory ships from the search if the concept of making first of all an arbitrary allotment say of $0{\cdot}25\ V_T$ to the superstructure is made and then after the depth of the main hull D is established, to modify this to a new depth D_A which provides a double bottom and a number of tween deck heights of the required height.

$$D_A = 1{\cdot}05\ (8n_d + 3) \text{ say} \tag{27}$$

The surplus volume within the main hull ($= C_W\ (D - D_A)B$) would then be transferred into the superstructure. This whole concept could be linked to a different method of establishing the VCG of the hull, which I hope to put forward in a forthcoming paper.

5. 14.

It is somewhat surprising to see such a good plot of machinery space volume with no appearance of power as a parameter. Presumably this can be attributed to all the ships being of approximately the same speed.

Does this not, however, suggest a better method of estimating machinery weight? First estimate the machinery space volume from a base of displacement and then apply to it a weight/unit volume which could be tabulated against power of various machinery types.

5. 15.

The formula for personnel volume brings me back to my earlier theme of occupational density.

7. 0.

It is extremely interesting to have the statistic that there were only 278 acceptable ships within an examination ranging over 82,944 cases, and the authors' provision of selection methods to reduce the number quickly to 278 and then to 18 is clearly an essential feature of any computer-aided design process.

The authors' comment on the difficulty of establishing the accuracy of the program because it already contains all the good data available to them, shows them to be most realistic in their outlook. I believe they have done a first class job for the Canadian Navy and would thank them most sincerely for this excellent presentation to us.

Mr H. Lackenby, D.Sc. (Fellow): In the first place I congratulate the authors on the development of this exploratory design concept including the wealth of useful naval architectural data which is associated with it. I would like to offer some brief comments on the latter.

I was interested to see that for $\overline{KB}$ Morrish's formula is used viz:

$$\frac{\overline{KB}}{T} = \frac{5}{6} - \frac{1}{3} \cdot \frac{C_B}{C_W}.$$

This is not a bad approximation, but it assumes a trapezoidal distribution of waterplane area with draught, that is, two straight lines with a knuckle arranged so that the vertical prismatic coefficient $C_{VP} = C_B/C_W$ is simulated.

In my experience a better approximation is given by:

$$\frac{\overline{KB}}{T} = \frac{C_W}{C_W + C_B} = \frac{1}{1 + C_{VP}} \tag{28}$$

This corresponds to a distribution of waterplane area represented by a continuous exponential curve where the exponent depends upon the vertical prismatic C_{VP}. The indications are that the trapezoidal approximation generally leads to a slightly higher estimation of $\overline{KB}$ than the exponential one and would give rise to an estimation of GM or metacentric height which would generally be on the optimistic side.

I would like to mention here that the background to this alternative approximation for $\overline{KB}$ was discussed at length in an article by Professor Telfer[11].

It may be of interest to note that this exponential approach is equally applicable to obtaining an approximation to the vertical centroid $\overline{z}$ of a ship's cross section where it becomes

$$\frac{\overline{z}}{T} = \frac{1}{1 + C_{SA}}$$

where C_{SA} is the sectional area coefficient.

In the section on performance estimation, I see that R_R (residuary resistance) from various sources is used in conjunction with skin friction estimated for the ship using the

ITTC line with an allowance of 0·0004. In this connection, I note that the Taylor R_R values are used as re-analysed by Gertler[8] using the Schoenherr formulation. This is perhaps a puritanical point and numerically it may not make much difference, but the authors may care to comment.

A final detail: I note that for multi-screw ships the maximum propeller diameter is taken as 0·875T and for single-screw installations 1·0T. The latter does not appear to make any allowance for clearance at the bottom of the screw or immersion of the blade tips at the top and I would like to ask the authors whether there is any special explanation for this as far as small warships are concerned.

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11. Telfer, E. V.: 'The Transverse Metacentric Height of Ships'. The Marine Engineer and Naval Architect, March 1922.

Professor E. V. Telfer, Ph.D., D.Sc. (Fellow): The conceptual approach to ship design adopted by the authors should not be made the Kipling way! No ship designer should be expected 'to watch the things he gave his life for, broken' and then have 'to stoop and build them up with worn-out tools'. It has to be admitted that many of a ship designer's tools are really worn-out and the electronic computer does little or nothing to rejuvenate or replace them! For example, the parabolic formula for vertical centre of buoyancy just given by Dr Lackenby is one which I published in Ref. 11 some 54 years ago, believing it then to be original, but now fairly certain it must be attributed to Frederic Chapman (circa 1780)! It has been frequently 'rediscovered'! The present authors use the Morrish formula, published in 1892 but clearly anticipated by Normand in 1863. Morrish, however, deduced his formula from a trapezium substitution for the vertical area curve whilst Normand deduced his from ship data but using the same parameters. In Ref. 11 I considered also the extreme case of the trapezoid substitution as representing a very full waterline, high rise of floor, form. The height above the base in this case is given by the expression

$$\frac{T}{3}\left[4 - \frac{(4\chi^2 + 1)}{2\chi}\right]$$

in which χ is the usual symbol for δ/α, the vertical prismatic coefficient. By remembering that the parabolic, trapezium and trapezoidal substitutions, in that order, give increasing centroid height, a designer can review his relevant experience in the light of basic geometry and the reassuring use of the correct form factor, namely the vertical prismatic coefficient.

In Ref. 11 a choice of six known alternative expressions for waterplane inertia coefficients was also considered. The Hovgaard now used by the authors was considered the best of these, but an extremely simple one which keeps turning up in continental practice which was probably due to W. Schmidt is $\alpha^2/12 = C_{It}$ was not included. This is clearly correct for a rectangle and also for a triangle where $C_{It} = 1/48$. It is slightly low between these limits but this serves as a margin in design work. It probably has a greater average accuracy than the authors' equation (2)!

Turning now to wetted surface calculation I am inclined to doubt the perspicacity of the authors' formula (9). A far simpler formula was given in Ref. 12. Its main advantage is that it combines the old Kirk and Mumford formulae through the correct introduction of the vertical prismatic coefficient and it assumes a trapezium substitution for the vertical area curve (as in Morrish) and is given by

$$S = LT\,(2\chi + B\,\delta/T) \qquad (29)$$

when χ is unity we have the Kirk formula and when $\chi = 0{\cdot}85$ we have the Denny or Mumford. The side area is $2LT\chi$ and the bottom $BL\chi$. When these are equal the area is a minimum and this occurs when $B\,\alpha/T = 2$.

The authors' formula (9) at first sight appears to be of the Froude type where

$$Ⓢ = (3{\cdot}4 + Ⓜ/2) \qquad (30)$$

This however can be much more fundamentally expressed by

$$Ⓢ = \sqrt{2\pi}\ \sqrt{Ⓜ}/\eta$$

This formula is due to W. Schmidt (Ref. 16) and is based upon the substitution of the half cylinder of equal displacement and length to the ship's. This gives the minimum wetted surface for the given displacement and the η term, known as the wetted surface efficiency.

I referred to this most recently in discussing Ref. 13. It was there shown that η was a function not of B/T itself but of mean beam, i.e. $B\alpha/T$ and not also of midship section coefficient but of the vertical prismatic coefficient. The problem was fully dealt with in Ref. 14. Turning now to the authors' formula (9) it is extremely doubtful whether it has any fundamental claim to accuracy, particularly as it includes midship section coefficient and omits waterplane area coefficient. The classic D. W. Taylor charts are also deficient in this respect!

In passing, it should be noted that formula (31) can also be written in the equivalent form

$$Ⓢ = \sqrt{2\pi}\ \sqrt{\nabla L}/\eta \qquad (32)$$

In applying either equations (31) or (32) the η values given in Fig. 38 of Ref. 12 should be controlled against accurate wetted surface data for the ship type in question and simple correction factors noted for future reference.

I am intrigued by the authors' Figs. 4 to 9. It is rewarding to see the resistance presentation therein adopted coming into greater use despite its now 43 year period of gestation, Ref. 15! However, I would not have separated wavemaking from frictional resistance in the way the authors have done. Since wavemaking decreases with increase of Ⓜ and frictional resistance does the very reverse, the total presentation is more discriminating since optimum Ⓜ values become immediately obvious. Moreover in this form it becomes more obvious that small Ⓜ values result in smaller fouling resistance per ton displacement for the same roughness growth.

Finally I would like to revert to the authors' Fig. 2 and say that I have always found it better to plot C_W (or α) to a base of block (δ) and not prismatic coefficient, since then for a given type of ship we can write,

$$\alpha = (1 - \Phi) + \Phi\,\delta) \qquad (33)$$

and hence,

$$\Phi = (1 - \alpha)\,(1 - \delta) \qquad (34)$$

in which Φ, the frame factor, uniquely characterises the form type of ship. For example, a high Φ factor means U shaped sections and low factors V shaped sections. To define a form adequately, however, it is necessary to distinguish the fore and after body Φ factors. For example in Todd's Series 60 the Φ_F is 0·90 and the Φ_A is 0·60. It would be of interest to know the corresponding Φ factors of the authors' C.E. model.

In conclusion I would like to suggest that some time in the future the Institution may be able to organise a Symposium dealing with the basic elements of ship design. The authors' work well illustrates the points which will arise in such a Symposium and has certainly lavishly whetted our appetites for more. Such a Symposium has just been proposed by the Japanese Society of Naval Architects to celebrate in 1977 their Eightieth Anniversary. It will be awaited with interest.

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Mr A. E. Reeves, R.C.N.C. (Fellow): The Forward Design Section of the Ship Department in Bath is responsible, among other things, for developing computer-aided design for British warships, and we supply design methodology for this purpose to Dr Yuille's team at ARL, Teddington which does the programming.

In computerising our preliminary design process we have been mounting separate approaches to the weight/cost/space aspects in one program and to ship geometry in another. Both are clearly essential to the concept exploration process in our opinion and should be interactive, although we still have to achieve this ourselves.

Our weight/space/cost program DOMINIC is built around the type ship or basis ship approach using triplet data for performance. The pure hydrodynamicists in Bath and at AEW Haslar take us to task for this, saying that we tend to throw away the propulsion possibilities in concentrating on weight and space at too early a stage in the design process in our program. This aspect continues to receive attention accordingly.

The authors' model is very good from this point of view as it does provide the basic ship dimensions of length, beam and draught with considerable opportunities for reconciling the conflicting requirements of high propulsive efficiency, good seakeeping and low cost. Our experience is that low cost makes for short fat ships whilst the other factors tend to demand length.

In reading the paper I found myself wondering whether the model had not gone too far in getting this aspect right at the expense of the other basics, space and volume, and in particular the three major items of crew accommodation, machinery volume and superstructure volume which account for about three-quarters of the total volume of the ship. It is our experience that ships of frigate type are space dominated and I think that the treatment accorded to these three items is relatively scant.

In particular I question the use of the rubber engine approach. The choice of gas turbines is very low at the moment—two or perhaps three at the most—engines of widely scattered power levels. The engines available have a large say in determining the optimum dimensions of ships in our experience. A minimum length of machinery space cut off factor ought to be included, and gas turbine uptakes and downtakes which occupy a relatively large volume also deserve separate treatment.

Finally there is no mention in the paper of interplay with ship geometry. The general arrangement drawing always has the last word in my experience. The judgement of the naval architect is still the most essential part of the process.

Mr W. A. Crago, B.Sc. (Fellow): As with all good papers, the authors have made their work look relatively simple, and one wonders why we have not had a paper of this nature in our Transactions before. Incidentally, I think it is interesting to note that a similar approach is used in helicopter design by at least one company, and the Lockheed 'Crash' program even seeks to optimise the design of the helicopter in the context of an aircraft crash.

I have one detailed comment to make with regard to Section 4.2. It seems that a fair degree of sophistication is used to obtain the residuary resistance. Then the frictional resistance is calculated with what appears to be adequate precision. These two are added together and then the authors make what appears to me to be a rather crude estimate of the appendage resistance by assuming an allowance of 20%. This allowance is quite large and therefore quite important, and it seems to be inconsistent to make such a gross assumption after doing the rather more sophisticated calculations on the other components of the resistance. It may be that the figure of 20% is justified by the authors' supporting researches, and if it is I am sure we would all be pleased if they would tell us about it. However, I would have thought that the concept exploration model might have been improved and made more internally consistent if the geometry of the appendages had been included in the program. Of course, the appendage resistance has always been a rather grey area, and I think that anything that the authors care to say on this subject will be appreciated.

Mr J. D. Brackenbury, R.C.N.C. (Member): I should like to make a comment on stability. As I understand it, the authors are saying 'Let us make sure that we have got at least a minimum acceptable GM after the maximum damage for which we allow. To achieve this we must start with a value of GM which exceeds the minimum acceptable damaged value by an amount equal to the loss of BM resulting from flooding'. This approach will admittedly satisfy the condition for retaining an acceptable GM after damage, but does not take into account at all any of the characteristics of the GZ curve either before or after damage. I suggest that fuller consideration needs to be given to statical stability characteristics even at this early stage in the design process.

A possible line of attack might be a development of the approach put forward by Professor Prohaska to the Institution in his 1947 paper. In this paper he derived a simple diagram from which residuary stability coefficients could be obtained by the designer to enable him to produce an initial assessment of the form of the GZ curve. With the proviso that the diagram produced by Professor Prohaska was based on merchant ship forms and a modified diagram would be required for warship forms, this would seem a profitable line to pursue. It would enable the designer to check his form at an early stage against, for example, the Sarchin and Goldberg Stability Criteria. Do the authors consider such a stability check feasible to contain within their program?

Mr B. N. Baxter, M.Sc., Ph.D. (Fellow): I agree that for shipbuilding design offices the most satisfactory method of warship design is to consider systematically the effects of changes in an existing successful basis ship, preferably one built in the designer's shipyard. The changes should not result in a ship which differs radically from the basis ship since this would make the new design suspect and although this traditional approach tends to inhibit innovation we have found few countries who are interested in innovative design. The first question most naval staffs ask is where they can see or visit the successful sister or basis ship. Another good reason for using a trusted basis ship is that with each successive repeat ship the changes in design and construction can be incorporated with the maximum of knowledge and minimum of disturbance and, therefore, a maximum of benefit and a minimum of cost.

Difficulty is foreseen in obtaining a computer program covering all the parameters which determine the final weight and volume of a modern warship since these are dependent upon, for example, weapon fit, size and number of helicopters, crew numbers and state of training and availability, endurance, speed, radar and aerial arrangements, type of main propulsion etc, and too large a number of variables will result in a solution which is not definite enough for a small warship.

The first problem facing designers of warships is still the determination of speed, power, endurance and seaworthiness and if there were available a reliable source of data on warship performance comparable to the BSRA information on merchant ship forms this would provide most of the information required by the designer at the preliminary design stage.

The seakeeping considerations given in Sections 3.7 to 3.10

are very interesting but their use for designers is limited because other considerations will have determined the length, freeboard and midship section coefficient of the new design. In particular, significant variations in length to avoid excessive pitching will not be possible because of economic reasons.

The paper states that the all gas turbine warship is only the first example of the method of concept exploration but I take this to mean that CODOG installations have been deleted from the choice available and we happen to believe there is great merit in this type of propulsion. In addition, the choice of gas turbines in this country is limited and the machinery installation is of necessity determined with relation to the available machines, e.g. Rolls Royce can at present offer:

(i) A Tyne engine with 5,000 BHP

(ii) An Olympus engine with 26,000 BHP

(iii) The Spey engine at 15,000 BHP which is not yet commercially attractive.

Therefore, the Olympus is the basic UK source for high power requirements and has been fitted as either a single engine in the case of the Yarrow Frigates, a double engine in the case of the Type 21 Frigates or a quadruple engine in the new through-deck cruisers.

The concept exploration optimum would more often than not involve a power requirement which could not be met from any combination of the three available power levels and would thus lead automatically to a non-optimum solution.

The conclusions with regard to supply of electrical power are not unexpected and the 1 kW per ton rule of thumb is quite acceptable for medium size ships, although it would not apply for patrol boats below 1,000 tons.

Whilst gas turbo-generators are as yet not in common use in this country the specific fuel consumption for gas turbine generators shown in Fig. 15 emphasises that gas turbines are not economic and consumption gets worse for smaller units. What it does not show is the different specific fuel consumption for different loads. When on passage it is unlikely that generators will be running at more than 50% capacity and, therefore, the specific fuel consumptions for gas turbines would be highly unfavourable compared with diesel generators.

I am surprised that equation (23) can give a good approximation to the total weight of electrical equipment and would, for example, expect cable weights to be of the form $a(k_1 \Delta P_g)$ since this depends on both installed power and displacement. The wide variations for electrical power shown in Fig. 3 for three ships each of about 4,000 tons displacement surely indicates that the cable weights in the ships could not be the same. Similarly, five ships with about 3 megawatts of installed power varied in displacement from about 3,000 to 8,000 tons and, therefore, must have significant differences in cable weights. Perhaps the authors would indicate under what heading cables are included in equation (23).

Whilst the concept exploration model provides a very useful design approach I believe that conventional small warships can be designed quicker and better using a basis ship. The methods outlined by the authors which include estimates of all the prime variables, such as stability, buoyancy, speed loss and performance could be used by design offices in yards who have not designed a warship and are looking for some basic method of doing so. In these circumstances, the information contained in the paper would be most helpful.

Professor W. Muckle, Ph.D., D.Sc. (Fellow): What I have to say is inspired by the remarks of Dr Lackenby and Professor Telfer. Quite a lot of the discussion has revolved around the Morrish formula. Actually while I think that this is a very unimportant part of the paper, I have found that if for actual ships KB/T is plotted against the ratio C_A/C_B, which is the reciprocal of the vertical prismatic coefficient it is possible to get a curve which is nearly a straight line and it is not necessary to make any assumptions. The advantage is that one is working from real ships, and the formula for KB/T would be of the form $A + B\frac{KB}{T}$. I am not quite sure whether this would go through the origin, but if it did then A would be zero.

I must thank the authors for a very excellent paper.

The Chairman then proposed a vote of thanks to the authors which was carried with acclamation.

WRITTEN DISCUSSION

Professor C. Kuo, B.Sc., Ph.D. (Fellow): It is not always easy for those of us who are not closely associated with warships to have an appreciation of the techniques used in arriving at the desired designs. In this respect, the authors have given us an opportunity to look into the approach being adopted in the naval studies. I can recall that in September, 1974 at the Stone Manganese Marine Conference, Professor K. J. Rawson suggested that computer applications have allowed the Navy to benefit from some of the major developments in merchant ship design and I am delighted to see computer-aided design being applied to warship design. I would like to ask the authors for their comments on the following two points:

(a) The approach given in the paper resembles the techniques adopted by Murphy, Sabat and Taylor[17] and since that period considerable work has been done by such authors as Nowacki[20], in which nonlinear optimisation methods have been used to tackle this problem. I would therefore like to know whether the authors have examined the applications of the latter methods and, if so, what are their experiences in applying them to warship design?

(b) In the concept exploration, I obtain the impression that the criterion for assessing the success of a design is performance as illustrated in Section 2.5. As I believe that the factor of constructional costs greatly influences the final choice of a particular design, I wonder whether the authors believe it is realistic not to incorporate the constructional costs into their computer design procedure?

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Mr I. M. Yuille, B.Sc., Ph.D. (Member): Several papers have been published on the concept design of commercial vessels but this is the first known to me on warship design. I congratulate the authors both on the thoroughness of their work and the lucidity of the paper.

In 1968, at a Seminar at Salford University, I read a paper on Optimization in Engineering Design[21]. Among the examples I used to illustrate the technique was one concerning the preliminary design of a cargo vessel, the characteristics of which were represented by empirical equations similar to those used by the authors. The experience gained during the work which preceded that paper gave rise to the following comments and questions concerning the paper under discussion here.

In the work mentioned I used a very efficient optimisation

technique that did not require the calculation of derivatives. It converged to an optimum design within a few hundred iterations (in contrast with nearly 83,000 by the authors' technique). The method always converged to the same global optimum design no matter where the search was started (provided that a start was made within the range of validity of the empirical equations used in the model). When the optimum design had been found, its sensitivity to changes of dimensions could be explored by means of a matrix centred on the optimum and the number of designs calculated again amounted to only a hundred or so at most. Thus, the reasons given by the authors in Section 2.1 for selecting a matrix type of search do not appear to be valid.

In fact, however, the method I have been referring to requires a smooth response function and breaks down if such functions are not used. Some of the empirical equations will not be smooth in practice. In particular the propulsive machinery of modern warships increases in size by large steps as illustrated in Fig. 17. At first I assumed that this was the reason for the authors' choice of a matrix type search but in Section 5.6 it is stated that the discontinuous function was approximated by a continuous one because the selection of a realistic machinery installation lay beyond the scope of concept exploration. Notwithstanding the difficulties mentioned in Section 5.6 I would like to suggest that the authors should persevere in this area because, as they say, the real situation is that in which ship size has to be matched to a limited choice of machinery installations. Their matrix search method should not break down under these circumstances.

Many other approximations are inevitable in numerical ship models of this nature and this raises the question of the overall accuracy of the procedure. In Section 7.1 the authors mention the possible choice of dimensions of a known ship to give an immediate check on accuracy of the model applied to that case. But they say that if enough data are available for the ship to be used as a test case, for this purpose, that ship has already been used in the data base of the model. Would it be possible to use all the data except one ship to create a model and then find how accurately it predicts that ship? Surely the authors had early models before all the data now used were available to them. Some fairly reliable estimate of accuracy is needed in order to give confidence in the results. Could the authors please give some figures?

Finally, the authors state in Section 2.1 that 'the chance of the C.E. models' optimum ship becoming the final design is small indeed'. Will they please elaborate on this? If cost was calculated (with sufficient accuracy) would it still be the case that the optimum (minimum cost) ship would not become the final design? If not, there must presumably be overriding constraints that must be satisfied and someone is willing to pay for this. What are these constraints? Could they be included in an improved model?

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Mr D. K. Brown, M.Eng., R.C.N.C. (Fellow): **This is a most interesting paper supported by a mass of convincing data. However, I feel that the authors have unwisely limited the value of their work by confining their objective to a search for the minimum size of warship. True, there are statistical relationships between size and both cost and complement but such relationships cannot usually be differentiated to give a slope. (This also applies to the more technical relationships.)**

For the type of ship considered, the range of possible dimensions and forms is usually very closely defined once operational limits are properly stated. Such limits might include:

Length: Maximum capable of fitting in available dry docks. Minimum from weapon or sensor layout.

Beam: Minimum from initial stability.

Draught: Minimum from propeller diameter (see later) and sonar immersion.

Internal Volume: Minimum from sum of compartment values. Subject to cost, there is no maximum.

Section areas: Forward there must be room for sonar, amidships for machinery (in particular, the gear box) and aft for shaft lines. Such section constraints lead to tight limits on the prismatic coefficient (Ref. 22 gives section areas in terms of C_p).

If these limits are stated as inequalities, the range of feasible shipforms is limited and it is possible to produce linearised equations for any desired performance parameter in terms of form coefficients over this range. A parameter of particular interest is the mean fuel consumption integrated over a typical operating pattern and this can be expressed as:

$$\text{Mean fuel consumption} = a - b\,L + C\,Cp + d\,T$$

It is essential to consider operating patterns for COGAG ships as the change-over speed from cruising to main turbines has such a marked effect on consumption and is itself a function of hull form.

Typically, such analysis will lead to three interesting ships:

(a) **The authors' minimum size ship.**

(b) **A much longer, fine ship with higher acquisition cost offset by lower fuel consumption, easier maintenance, higher speed etc.**

(c) **A deep draught, but still slender form which shows up well in seakeeping and sonar operating conditions[23].**

While absolute cost estimates are very difficult it should not be impossible to estimate the difference between these alternatives.

Turning now to more detailed points,

CP Propellers: These are limited by the requirement for blades to turn through each other and by pressure loading. It is unlikely that a satisfactory warship design can be produced if the diameter (metres) is less than:

$$1/5\sqrt{\frac{P_s/\text{Shaft (kW)}}{V\text{ (knots)}}}$$

Prismatic Coefficient: The scope for varying C_w independently of C_p is small and attempts to do so may well adversely affect GZ. I prefer to use:

$$C_{It} = 1{\cdot}033\,C_p - 0{\cdot}10$$

For 16 modern warships the standard error was 4·7%. This expression, together with the authors' Fig. 8, suggests that C_p should be regarded as a stability parameter rather than one of resistance. This becomes even more true when damage stability is taken into account as the very non-uniform distribution of buoyancy associated with low C_p forms can raise problems, particularly when trim is taken into account.

The effect of C_p on usable internal volume is very marked. The low C_p form will give spacious machinery spaces, probably bigger than needed, associated with unusable, fine ends. On the other hand, the low C_p form scores heavily at the change-over speed and can give marked fuel consumption advantages. A suitable compromise is both difficult and rewarding to find.

Wetted Surface: The authors' expression appears unnecessarily complicated for this stage of a design. The AEW, Haslar formula:

$$\text{Ⓢ} = 3{\cdot}4 + \frac{\text{Ⓜ}}{2{\cdot}03}$$

is within 2% for a wide range of warship forms.

Hull weight: The mass of hull structure and fittings is very closely given (in tonnes) by:

$$0\cdot925\ (L.B + B.D + L.D) \quad \text{(metres)}$$

Having completed his study, the naval architect should go back to the naval staff and challenge the validity of the initial, operational limits should the study indicate advantages in relaxing any one limit.

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Mr D. J. S. Beck, B.Sc. (Member): The authors have presented an interesting paper on a very difficult subject and I was particularly interested in the approach to the determination by a simple means of seakeeping for a hull form, since this is one area most wanting in simplification for initial design requirements. However, I was a little worried by the use of warship payload as a factor in the determination of an initial design and I would therefore like to know how the authors relate the warship payload weight to the physical distribution of the weapons, radars, trackers and communication aerials bearing in mind the problems of arcs of fire and interference between various aerials and radars. Naturally, the simple answer would be to have a large ship but, as warship designers will appreciate, the present trend, mainly through economics, is for smaller ships, particularly those for the developing nations. The problem therefore of providing a suitable weapon package on a compact, cost effective warship is extremely important. First impressions are usually very important and it is essential that the facts, however brief, are accurate and can be developed within the stated parameters, into a functional warship.

Mr D. J. Andrews, M.Sc., R.C.N.C. (Member): In welcoming this very necessary paper on the vital and little investigated field of the early stages of ship design it inevitably provokes some very fundamental questions. I would raise these questions under two main headings:

(a) Is the approach to ship design proposed in this paper philosophically sound?

(b) What is really required of a truly useful tool for the initial stages of the ship design process?

On the first point it must be stated that the authors do not seem to have satisfied the elementary basis of scientific method. Popper [24] has elucidated this by saying that scientific methods should have the quality of testability. Now it may be felt that this is a rather Olympian and esoteric stance to take towards a basically practical tool, but I feel the lack of proof of the method displays a fundamental weakness, which such CAD approaches to ship design must deal with if they are to be really valuable tools. The fact that we naval architects do not pose such questions about the nature of ship design is an indication of the lack of understanding or even desire to understand the ship design process [25].

Considering the particular point of testability, in this approach of concept exploration the authors do not give any indication that they have tested the ability of their tool to produce viable designs. Have they for example tried to produce a ship design which is not already within the 'data bank' but has actually been realised and see how close they get to reality? One suspects that this would only produce a reasonable answer for culturally similar designs to those already implicit in the broad assumptions of the program. For example, as this is a Canadian program, if the DDH 280 destroyer escort design was not used in providing the data for the program then maybe it could be produced based as it is on the actual extrapolation from the St Laurent design [26]. However, should the features of the Russian 'Krevak' class destroyer be inputed then it is highly unlikely that the program could produce the actual answer, based as this design is on a different 'pattern', not in the 'data bank', and also a quite different ordering of design priorities from western warships [27]. Such a model will not help with real step changes in design evolution. For example, how would it have dealt with the change in destroyer concept that occurred when the Hunt class destroyers had the destroyer break of forecastle moved much further aft or the effect of the decision to extend repair by replacement to its present level of space demand, or a change in the philosophy of watertight sub-division, or say the degree of back up in 'essential' systems, or having the Action Information Complex high or low in the ship, or the degree to which electronic sensors take precedence over other armament features (Eckhart [28] discussed this in relation to the US Navy LCC 19), or effect of certain levels of modularisation—and these are only some of the changes that one can see now, what about the future questions? This I feel reveals one of the inherent dangers of any computer model; it can be used without understanding the very real constraints that are within the particular model. This is bad enough with a structural or dynamic analysis, how much greater is the danger when the computer is used at the conceptual stage of the design?

However, it is not my intention to denigrate computer methods completely, as a latter day Luddite, for it would seem that the only way forward in solving the real problem of the initial stages of ship design is by use of sophisticated computer techniques. But before we do so we must be clear what it is we are trying to achieve and hence my second question. Here there seems to be two fundamental areas, one concerns synthesis and innovation, the other the design environment and the constraints on it. Caldwell's [29] recent paper on the education and training of naval architects admitted the lack of any clear method to foster creativity. However, in the discussion on Caldwell's paper [30] it was suggested that the approach used by some Architecture Schools to this may be relevant to teaching a more creative approach to ship design. The approach suggested by this paper follows the classical theory of the ship design process and it is doubtful if such a picture of the design process and a reliance on a 'basis ship' is sufficiently broad to cater for the modern design environment and its complexities both external (i.e. every system is part of another system and interacts with others) and internal (i.e. effect of new ideas, technologies etc. on the system) to use Jones' terms [31] referring to design methods in general.

What is really required of a computer aid to design is the ability to provide quick realisations of quite different solutions possibly arrived at by several (appropriate) design strategies. Thus the designer must be given the freedom to synthesise solutions and then analyse their consequences in broad terms. This means that such a facility must allow the designer to use a graphical picture and hence innovate. Secondly his creativity must not be limited by the hard numbers within the model which are readily dealt with by the computer. For these hard numbers are usually less significant to the design solution than the soft ones (from the degree of flexibility in the design to the 'political' pressures on the design organisation in its use of resources) and these less tangible factors generally constitute the actual constraints on the design. Until we have CAD methods that allow the designer this freedom to see all these effects on the design and clearly state to the user the limitations each method is imposing on the designer, then such approaches can only be treated with the utmost caution.

The authors are to be thanked for provoking such serious questions on the initial ship design process. However these questions will only be faced when the broad question of the ship design process in toto, the synthesis of designs and the full constraints on the design process are at least clearly appreciated. This is a necessary starting point to reaching an understanding of ship design which is vital to naval architects if they are to cope with the ever expanding possibilities that are within the orbit of ship design.

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Mr G. H. Fuller, R.C.N.C. (Fellow): The authors are to be congratulated in completing a design spiral in the computerising of ship design by showing the merit of mechanising the traditional evolutionary process of design from the base ship to the new concept. This is a practical approach to the real world recognising the human interaction and innovation which are difficult and expensive to formulate in the strictly mathematical terms necessary for the complete computerisation of the process. The result, which can be criticised as relying too much on traditional empirical and approximate relationships, is at least a process in which the designer is fully aided by the computer, yet never loses control of the process. This is a vital point in any computer-aided design concept. Once the chosen design has emerged, the power and speed of the more complex programs can be applied to validate the choice fully.

It would be of interest to ask if there is any work on the application of elementary computer-graphics to take these first approaches to the design on to fundamental arrangement questions such as weapon arcs of fire and length of machinery packages. Secondly, are the authors exploring trends and sensitivity analysis in the areas of structural material variations, for example the use of high strength steels and the merit of thick keel sections for volume constrained high superstructure ships? Finally, the authors have re-drawn attention to the very crucial role played in the basic design and life cost of not only the complement but also its life style; this area alone would merit a separate computer-aided study.

AUTHORS' REPLY

INTRODUCTION

We are most grateful to the 16 contributors who have added a great deal of value to our paper. Their comments range from broad questions of philosophy to specific technical detail and it would take another paper to provide satisfying answers to all the points raised. In this reply we will attempt to clear up some misunderstandings and further explain some of the features of our C.E. model. We do not intend to justify particular expressions we have used in the algorithm, relative to alternatives proposed by contributors. As we have stressed, our model is flexible and specific equations can readily be replaced as improvements are suggested by the data at hand. Indeed, SHOP MOD 4, the current model, already differs in much detail from SHOP MOD 3, the model described in the paper. Our paper was written to advocate our approach and our methodology, not the specific details of our algorithm.

CONCEPT EXPLORATION

Design Philosophy

We were particularly pleased to have Cdr Roushorn and Lt Cdr Wight comment on the actual use of the C.E. model in conceptual design practice. They have clarified and illustrated the roles that the model can play and have emphasised the importance of applying experienced judgement in its use.

We hope that Dr Baxter found these comments useful, because he has clearly misunderstood our objectives when he 'believe(s) that conventional small warships can be designed quicker and better using a basis ship'. We are not offering him an alternative, rather an additional tool to apply before he begins to use his basis ship. We can well understand that, in some commercial practice, the requirements for a new warship may be so similar to those of a previous design that this additional tool will be considered superfluous. However, it is so quick and easy to use and provides such a wealth of guidance information, that if Dr Baxter had it available, we feel sure he would use it. Its real value lies, of course, in design situations where one faces radically new operational requirements and is uncertain of the choice of a basis ship, as illustrated by Lt Cdr Wight.

We suspect that this misunderstanding triggered Dr Baxter's worry about the accuracy of weight and volume estimates. We agree that the detailed data that can only be obtained from a basis ship is essential to the concept development and subsequent design stages, but believe our estimates to be adequate for concept exploration.

We are not sure how seriously we are supposed to take Mr Andrews' comment that we have not satisfied the elementary basis of scientific method. Perhaps he would be less worried and reach a closer understanding of the nature of ship design if he accepted the fact that design is an art, aided by scientific tools, of course, but certainly not a science in itself. Moreover, a tool like ours, which strings together a great number of estimates and approximations, and relies upon the designer's judgement in the interpretation of its results, makes no claim to be fully scientific. This does not mean, however, that the approach is philosophically unsound, as Mr Andrews implies. Indeed, it has more of the elements of scientific method in it than a lot of other techniques now used in ship design. We believe that in a process as complex as warship design, it would be fundamentally unsound <u>not</u> to allow the experienced judgement and art of the designer to be brought to bear.

Perhaps Mr Andrews has been unduly worried by our rigorous statement that the accuracy of the method cannot be scientificially tested because all the available data have been incorporated in the model. In practical terms, and in answer to Dr Yuille also, the model has duplicated existing ship characteristics generally within 5% and with occasional errors of 10%. We also have Lt Cdr Wight's statement that it gives results within 10% of those obtained by more detailed methods of calculation. More important is its relative accuracy as design variables are changed, and this we believe to be closer to 5%. However, we emphasise that it is difficult to claim true 'testability' for any ship design method. Seldom does the designer know the real accuracy of the data in his bank. Finally, we pose the counter question, how accurate should a conceptual design method be?

The use of a wide data base including many types of ships from several nations has the effect of smoothing out individual discrepancies, and the effects of 'cultural similarity'. Contrary to Mr Andrews' expectations, the model is equally at home with ships of different nations, provided the optional inputs are intelligently used, and herein lies the key to its use in design evolution.

Mr Andrews asks how the model could 'deal' with a number of changes in design concept. The model cannot 'deal', but the designer can use it to help him, once he has assessed the effect of a proposed change on the model inputs. The model can then tell him whether his change has set him a problem of stability, of powering, of space, etc, and the relative impor-

tance of these factors. Lt Cdr Wight has provided a good example of just this sort of use.

We cannot offer useful comment on Mr Andrews' final philosophical paragraphs, except to suggest that we have to learn to walk before we learn to run. Our paper only ventures to suggest how we might toddle.

Design Objectives

Mr Watson, Professor Kuo and Mr Brown regret the lack of a costing algorithm. So do we, and perhaps our comment in Section 1.2 was not made with sufficient force. We adopted minimum size as the objective of our search procedure, rather than minimum cost, only because of a lack of adequate costing data. Our subsequent discussion of the correlation of costs and complement with ship size was only to help justify this enforced substitute, not to suggest that minimum size was a more desirable objective.

Indeed, we heartily endorse Mr Watson's view of the need to violate what he so aptly christens 'Admiralty Law', if real progress is to be made in warship design. Nevertheless, we maintain that maximum operational weight ratio (W_u/Δ), and the alternative criteria the model offers (maximum operational volume ratio and maximum transport effectiveness), remain valid measures of the relative efficiency of ship designs at the concept exploration stage, and provide the most useful basis for evaluating design trends.

Where the designer must exercise discretion is in setting his inputs conservatively so that he is not forcing 'a quart into a pint pot', and in evaluating the results, not automatically accepting the minimum sized theoretical optimum. He must, for example, anticipate payload expansion, both during the design process, and for the expected mid-life conversion.

As we see it, the minimum sized ship sets a point of reference—a target for the designer to aim at—and the logical point of departure for the trends of design variables. Using that point of reference he can then select a basis ship and sketch his general arrangement. Because the model has involved only rudimentary total volumes (we agree, Mr Reeves), whereas different parts of the ship have widely different 'real-estate' values, he will almost certainly find that there are changes he has to make to accommodate all his requirements. The trends will tell him how to do this with the least penalties, and how and where to add sensible design margins (at this stage Mr Watson, not within the C.E. model search).

He now has a new set of inputs which he can either use in a second application of the C.E. model, or use directly in a basis ship approach for the concept development stage. This choice will largely depend on how close his basis ship lies to his current set of inputs.

We hope that the above expansion of the second paragraph of Section 7.1 will help to explain to Mr Reeves, Mr Beck and Mr Fuller, how we see the general arrangement entering the C.E. process. We certainly agree that it often 'has the last word' in settling many features of the design. We would go further and suggest that in most cases it will be necessary to sketch a very preliminary layout at the outset, in order to determine inputs to the C.E. model such as the required operational volume, superstructure volume and operational constraints on the basic dimensions. Thus it may have both the first and the last word, but this does not detract from the value of the C.E. model.

We see subsequent work with the general arrangement, using computer-graphics, as part of the concept development stage, because we feel we will have to rely on the detailed weights and volumes data of a basis ship for much of this. Unfortunately, this remains very much in the realm of hopeful future plans, as do the other topics suggested by Mr Fuller.

The foregoing also answers Dr Yuille's question as to why the C.E. model's optimum ship is unlikely to be the final chosen design. This should remain the case even if the optimum were the true minimum-cost ship, although the designer would then doubtless have a more difficult administrative job on his hands in justifying departures and introducing adequate margins. For dealing with Comptrollers, it may be a blessing in disguise that it is so difficult to arrive at a true minimum-cost ship!

We hope that we have corrected Mr Brown's impression that our objective is confined to a search for the minimum size ship. This is our point of reference, but it is the trends about that point which are most valuable to the designer. We cannot agree with him that the range of dimensions and form are closely defined by operational limits in our practice, and indeed he himself suggests that such limits should be challenged if the penalties so warrant. The sensible ranges should at least be explored, and there is scope within the model for introducing all the limits he suggests.

Search Technique

In answer to Professor Kuo, we have examined the work of Nowacki and others who have developed highly efficient optimisation procedures. We were not aware of the particular paper mentioned by Dr Yuille[21]. As described in the paper we were originally using a series of discrete machinery installations, resulting in discontinuous functions for weights, volumes and fuel consumption, and these caused difficulties with some of the search techniques we tried.

However, we did not pursue solution of these problems after we had tried the simple matrix type of search, because we found that users appreciated the wide scope of the presentation of 'possible ships' and 'violations' made practical by this method. Although mathematically far less efficient, in practice it costs very little to run through a full matrix in a program as simple as ours.

Now that we have had to resort to 'rubber' engines, we agree with Dr Yuille that our earlier problems would not arise, but we also agree with his suggestion that we should try to return to discrete installations. Moreover, unless the program becomes much more extensive, we would be loath to abandon the additional information available in a matrix type of output.

NAVAL ARCHITECTURE

Program Weaknesses

We turn now from the broader aspects of concept exploration to the techniques of naval architecture used in our program. The discussion of these falls into two main categories. Some discussers have unerringly put their finger on weaknesses in our algorithm, mostly caused by a lack of data. Others have put forward alternative formulations in areas where we are currently satisfied. Their contributions are no less valuable, and indeed, as we gain experience, we may no longer remain satisfied.

Surprisingly, no one contributed suggestions in the area of seakeeping, which we state in the paper to be the major shortcoming of our model. Possibly this is because we reported, orally at the meeting, on the improvements we were introducing in SHOP MOD 4, and a brief outline of these follows. The other weaknesses that we acknowledge are our treatment of volumes, discussed by Mr Watson and Mr Reeves, our use of 'rubber' machinery (Mr Reeves, Dr Baxter and Dr Yuille), and our powering allowances (Mr Watson and Mr Crago).

Seakeeping

The seakeeping studies mentioned in Section 3.6 have come to fruition, and a much improved algorithm is included in the current SHOP MOD 4 program.

Thirteen hull form parameters are used to define the curve of sectional areas, the waterplane and the hull's profile. Lewis-form sections are then assumed and strip theory is used to calculate motions in a head sea of a specified spectrum at a defined 'sea speed'. To clarify this, the operational inputs state the speed that is required to be maintained in a

certain height of sea. We then specify the typical spectrum based on Station India data.

From the calculated motions, estimates are made of the probability of exceeding an acceptable level of vertical acceleration at the bow, of the probability of slamming, and of deck wetness.

Parametric studies have shown that the six independent variables used in the MOD 3 model in fact cover the major influences of hull form on seakeeping, bearing in mind that the other seven parameters used in our seakeeping model are not really independent. They are constrained in a practical design by the primary parameters. For MOD 4, typical values of these seven secondary parameters are defined for each of the three speed regimes, corresponding to the three broad types of hull covered by the model.

The calculations take too long to be incorporated directly in a search program. Instead, second-order response surfaces were computed from the results of the parametric studies, and the search program simply computes the seakeeping probabilities from the response-surface equations.

In the DESCRIBE mode, MOD 4 simply outputs the resulting probabilities. In the SEARCH mode, a threshold probability level is added to the constraints, thus rejecting ships with high probabilities of slamming or excessive accelerations. In the case of deck wetness, rather than rejecting a violator, we calculate and output the additional bow freeboard needed to bring the probability down to the threshold level. The designer can also, if he wishes, select his 'best ships' to be those with the lowest probability of slamming or excessive bow acceleration.

Although this is a comparatively crude model, starting to think in terms of seakindliness and motion constraints at the very outset of the design process we believe to be a significant step in the right direction.

Space and Volume

We agree with Mr Reeves that our treatment of volumes is rather rudimentary, but we wish he had given us some concrete ideas for improving it. One of the problems is that space-domination is a comparatively recent phenomenon in warship design, and data are scarce. In principle, of course, it is a simple matter to go back to past general arrangements and analyse volumes, but in practice this is of dubious value because of changing priorities for the use of space. Indeed it is these changes that are responsible for today's volume constrained warships.

What is really needed is some system of weighting the value of spaces in different parts of the ship, whereas the C.E. model works only with total volumes. In this regard, Mr Watson's suggestion of a modified hull depth, which is a discrete number of deck heights plus an appropriate double bottom, is very interesting. He is also correct in criticising our treatment of the superstructure. Frankly, faced with the wide variation seen in modern warships, we took the easy way out by making both its length and its volume optional inputs, but we acknowledge the difficulty this imposes on VCG estimation. We look forward to studying Mr Watson's promised new method.

We cannot agree with Mr Watson's suggestion that machinery weight might be better estimated from machinery volume. Indeed, we tried to do this during the model's development, without success. One can achieve some correlation of weight with the length of machinery spaces, but there is a clear tendency for the breadth and height of these spaces to be uncorrelated with their contents. It is simply that these spaces normally extend to the sides of the ship and to the next convenient deckhead, on the grounds that any excess space is marginally useful for other purposes and is best used to improve accessibility to the machinery.

Choice of Machinery

Regarding 'rubber' engines, we cannot really add to the comments already made in the paper, in reply to Mr Reeves, Dr Baxter and Dr Yuille. We agree that discrete installations should be used, but our early attempts were unsatisfactory. More detailed designs of typical gas-turbine machinery packages are being worked up by the Naval Engineers, and we shall try applying them. Depending on the inputs required however, it is not clear to us whether their use belongs in the C.E. or the C.D. stage of design.

One should bear in mind that a C.E. search output provides data on a broad range of ships. Even among the few 'best ships' defined at the end of the output there is usually a fair spread of estimated power levels. Selecting ships that are appropriate to the available plants is part of the designer's interpretation of results, and at worst will involve a repeat run with judiciously changed inputs. Dr Baxter's comment that the C.E. optimum would more often than not lead automatically to a non-optimum solution is correct, but not in the sense he implies. If there is no suitable power plant available a non-optimum solution is hardly the fault of the C.E. model. Indeed the C.E. model can show the designer what options he has in adjusting his design to an appropriate power level, and this information may be sufficiently valuable to warrant the use of 'rubber' engines in the opening C.E. stage.

Incidentally, the lack of diesel options for cruise engines and generators is not an oversight, but a conscious decision that this particular model would be for all gas-turbine powered ships. No final Canadian choice or recommendations are implied by this, however.

Powering Allowance

Mr Crago asks for more details regarding the powering allowance of 20%, stated in the paper to account for 'appendages and service conditions'. Frankly this is a composite allowance which correlates the results of our resistance and propulsion calculations to give final installed powers that are consistent with existing ship data. No doubt it covers a multitude of minor errors and allowances. Although it may seem a large correction, it is applied consistently from one form to the next and one must bear in mind that the form of appendages will not be known at the C.E. stage of design.

Mr Watson has a good point in suggesting that different appendage allowances should be used for single and twin screw ships. Our program was originally confined to twin screw ships and subsequently expanded. We have inadequate data on single screw warships to warrant reducing the composite allowance, however. Incidentally, in answer to Dr Lackenby while on the subject of single screws, warship propellers sometimes project below the keel.

In general, our feeling is that the complex question of powering allowances can only be treated statistically at the C.E. stage, and that it will take time to build up sufficient experience in the use of these models to arrive at the best figures.

Alternative Estimates for Hydrostatic Parameters

We are grateful to Dr Lackenby, Professor Telfer, Professor Muckle and Mr Brown for providing details of their preferred methods for estimating KB, C_{It}, C_W and wetted surface. We are not sure that we understand Professor Telfer's reference to Kipling; there is often a thin dividing line between a worn-out and a well-proven tool, and we certainly plead not guilty to breaking anything he gave his life for.

The variation between many of these estimates is small, and provided they involve the correct variables, any of them is likely to be satisfactory for the relative comparisons required in concept exploration. We look forward to a possible future Telfer-Schmitke confrontation on parameters dictating wetted surface(4), but feel it would be out of place here. Our advice to the designer would be to adopt those formulations which best fit the particular data base he is using for his model, provided always that this base spans the full range of variables over which the model will be used.

In reply to Mr Brackenbury, it was a conscious decision to

adopt only initial stability checks at the C.E. stage, and take up questions of stability at large angles, icing and dynamical stability as part of the C.D. process, when general arrangement and lines plans are available. We might change our view if an improved method of handling volumes incidentally provides us with a better definition of the hull above the waterline during the C.E. process, but our experience is that many factors affecting stability remain undefined at this stage. We have had no experience of Professor Prohaska's approach and cannot comment on its application to our model.

Resistance and Propulsion

***We thought we might be afforded a favourable comment from Professor Telfer on our presentation of residuary resistance coefficients.* These are separated from frictional resistance for the convenience of storing a single set of data in the computer for each speed regime, or ship type. The use of Ⓜ as an independent variable in the search procedure reveals the influence of this parameter on powering.**

In reply to Dr Lackenby's question on frictional resistance, of the four systematic model series used in the program [3, 6, 7, 8], only the Taylor-Gertler data were analysed using the Schoenherr coefficients. The other three are based on the *ITTC formulation*, and in practice, *most small warships fall* within the regimes of these three. Since the numerical differences in any case are small, we decided to adopt the ITTC line for all cases.

Mr Watson comments on the Lloyd estimate of speed-loss in waves, and the explanation does lie in the limits within which this holds. Actually, in SHOP MOD 4 it has been replaced by a more recent formulation by Lewthwaite of AEW, to whom we suggest he refers for details.

Regarding Mr Watson's comment on our estimation of propeller efficiency, it does not seem 'round-about' to us. Perhaps we are influenced by previous work in applying Newton-Radar propeller data, where it was important to estimate optimum diameters first, because we were not restricted in size. Having the data analysed in this form obviously made it convenient to follow the same approach for SHOP MOD 3. We have no experience of Emerson's formula, but instinctively feel happier with the parameters included in our method.

***Both Mr Watson and Mr Brown suggest that final performance should consider endurance under both cruise and high power conditions.* One of the improvements introduced into MOD 4 is the calculation of a 'mission endurance', the *mission* being defined by the proportion of time spent at four different speeds.**

CONCLUDING REMARKS

In case we have given the wrong impression with incomplete replies to many of the interesting and valuable points raised in the discussion, we would like to re-emphasise that our reason for writing this paper was to introduce the idea of 'concept exploration', and not to advocate specific details of our program. Indeed, we stress the need to keep such a program flexible, so that it can respond to differing needs and absorb new data as they become available.

Moreover, each different design agency will have its own views on how much detail it is desirable to introduce at the C.E. stage and how much to leave to the more conventional calculations of the C.D. stage. Such decisions are part of the art of design. Let it also be perfectly clear that what we are advocating is the addition of new outside turns to the design spiral. Concept exploration is not a substitute for existing design methods.

Finally, we must stress that, like all powerful tools, the C.E. model must be used with intelligent *caution. In no way does* it relieve the designer of decision-making authority or responsibility. *It* can provide him with the data he needs to make a very broad investigation of design alternatives; it *can also swamp him with irrelevant data if he uses it* unwisely. The assessment of the alternatives rests entirely upon the designer, however, and this is as it should be. No tool or computer can substitute for the experience and judgement necessary to design a good warship.

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13. ABSTRACT

This paper describes a versatile tool for the designer of small warships (1000-6000 tons), intended for use in the opening phase of the design process. Known as a "concept exploration model", it provides an alternative approach to the usual immediate reliance on a "basis ship", enabling the designer to explore a wider range of design concepts.

To calculate performance and other design characteristics from an assumed set of ship dimensions, a simple algorithm has been developed using data derived from a number of successful small warships. This has been programmed for a high-speed computer in such a way that a search can be made over a wide range of assumed dimensions, to determine a hypothetical "optimum ship" for specified operational objectives. More importantly, the trends of design behaviour around that optimum are clearly illustrated.

The concept exploration model is an advanced slide-rule, intended to relieve the designer of drudgery, and to provide him data in the quantities made possible by modern computers, yet in a form he can assimilate. In no way does the model relieve him of decision-making responsibility. Nor does it compete with more extensive computer-based methods developed for subsequent phases of the design process.

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